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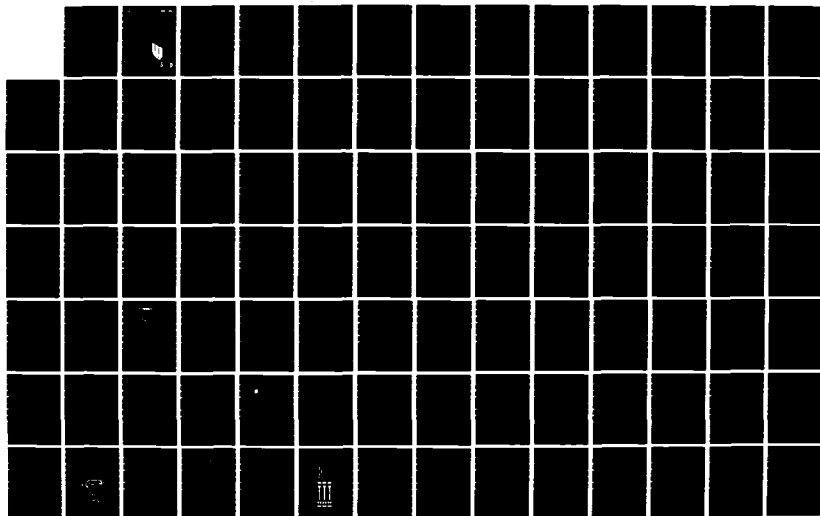   PROCESSES AT FIXED ARMY IN. (U) CONSTRUCTION
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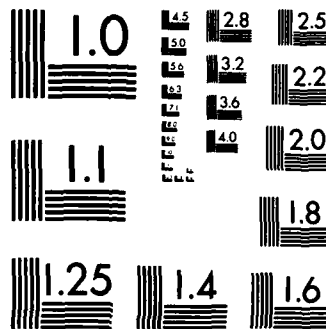
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Construction Engineering
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AD-A157 306

EVALUATING AND IMPROVING WATER TREATMENT PLANT PROCESSES AT FIXED ARMY INSTALLATIONS

by
L. E. Lang
J. T. Bandy
E. D. Smith

Research was conducted to determine processes at Army water treatment facilities that may be inadequate to meet recent regulatory requirements on potable water; develop a method of relating treatment processes with treatment plant inadequacies and identifying design, operation, and maintenance criteria that could be altered to solve problems and improve performance; and present, in an understandable form, proven new technologies and operational changes that will help solve problems and improve performance of Army water treatment plants.

It was found that the areas where regulatory requirements for potable water most affect Army water treatment plants are: corrosion, sludge handling and disposal, iron and manganese removal, trihalomethanes, high fluorides, high salinity, high nitrates, and coagulation/flocculation/clarification. Processes related to these problem areas are discussed. Trace organics were also identified as a problem area and are discussed in USA-CERL TR N-85/11.
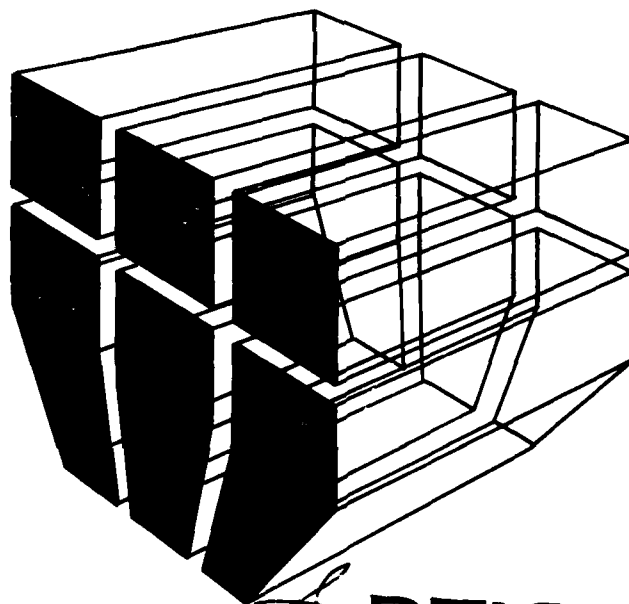
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Research was conducted to: (1) determine processes at Army water treatment facilities that may be inadequate to meet recent regulatory requirements on potable water; (2) develop a method of relating treatment processes with treatment plant inadequacies and identifying design, operation, and maintenance criteria that could be altered to solve problems and improve performance; and (3) present, in an understandable form, proven new technologies and operational changes that will help solve problems and improve performance of Army water treatment plants.

(Continued on next page)

BLOCK 20. (Cont'd)

Information was gathered from personnel at 44 installations, the Major Commands, the Facilities Engineering Support Agency, and the Office of the Surgeon General to determine which treatment processes are unable to meet regulatory standards for potable water. New technologies for processes affected by these regulations were investigated for possible application to Army facilities. Army and municipal plants that use these new techniques, along with advantages and disadvantages reported, are presented.

A systematic approach was developed for installation personnel to relate operational problems to specific water treatment processes and to identify key design, operation, and maintenance criteria that can be altered to solve problems and improve performance. This approach is comparable to a portion of the Composite Correction Program developed for wastewater plants by the U.S. Environmental Protection Agency.

It was found that the areas where regulatory requirements for potable water most affect Army water treatment plants are: corrosion, sludge handling and disposal, iron and manganese removal, trihalomethanes, high fluorides, high salinity, high nitrates, and coagulation/flocculation/clarification. Processes related to these problem areas are discussed. Trace organics were also identified as a problem area and are discussed in USA-CERL TR N-85/11.

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**EVALUATING AND IMPROVING WATER TREATMENT PLANT
PROCESSES AT FIXED ARMY INSTALLATIONS**

1 INTRODUCTION

Background

Federal and State regulatory agencies have promulgated requirements to control toxic substances and contaminants in public water supply systems. These requirements also apply to water supply systems at Army installations. Regardless of what contaminants the raw water contains, the water treatment plant must treat the water to meet the requirements. Existing treatment systems are often not adequate to provide an acceptable water supply without extensive operational adjustments or expensive capital improvements. Many have used the same equipment and operating procedures for decades, but now must face problems such as drinking water that contains trihalomethanes (THMs) and the need to stabilize the water to prevent corrosion of pipes and release of contaminants.

Many Army installations have water treatment plants more than 40 years old. The aged condition of these facilities means that corrosion is widespread, and metals released from pipes may be a health hazard. Sixty-eight percent of the installations surveyed in this study stated they have corrosion problems. Problems with high iron and manganese content; sludge disposal; control of THMs; and high levels of fluorides, salinity, and nitrates were also noted. High iron and manganese levels are a particular problem because minute amounts can cause unacceptable taste, odor, and color. Sludge has become an issue because of regulations on its disposal. High THMs, fluorides, and nitrates cause health problems. High levels of nitrates are not confined to installations in the United States; they are also found in water supplies at bases in the Federal Republic of Germany.

Since existing Army technical manuals do not comprehensively address these concerns, there is a need for information on how to upgrade facilities and/or operating procedures to meet regulatory requirements and lower operating costs.

Objective

The objectives of this study were to: (1) identify processes at Army water treatment facilities that may be inadequate for meeting recent regulatory requirements on potable water; (2) develop a method for relating treatment processes with water treatment plant inadequacies and for identifying design, operation, and maintenance criteria that could solve problems and improve performance; and (3) present, in an understandable form, proven new technologies and operational changes that will help solve water treatment plant problems and improve their performance.

The report is intended as a reference guidebook for Facility Engineers and others concerned with the design and operation of water treatment plants at fixed Army installations.

Table 7

Determining How to Improve
Existing Clarification to Control THMs

Jar Tests

- Use ultraviolet absorbance as indicator of organics removal.

- Vary coagulant or lime dose.

- Vary pH.

- Try cationic polymer or clay plus cationic polymer.

- If using lime, try adding alum or iron.

Plant Tests

- Measure THM levels in raw and finished water for normal treatment and with modification.

- See Table 9 for further evaluation of plant tests.

- Higher than stoichiometric coagulant/lime doses are generally needed to enhance THM precursor removal.

- Cationic polymers can broaden the pH range in which coagulation is effective in removing organic acids.

- Adjusting pH of water before chlorination also helped control THMs.

- New laboratory and pilot studies are discovering appropriate types and doses of coagulants and coagulant aids to remove THM precursors during coagulation. This is a promising area in THM control as new coagulant aids are developed.

Moving the Point of Chlorination

Plant Experience

A number of facilities have moved chlorination to a later step in the treatment process, such as before or after the filters, in order to reduce the contact time between chlorine and organics. Since the coagulation/sedimentation process removes some organics and chlorine-demanding substances, the water is of better quality when the chlorine is applied. Thus, the dose can be significantly reduced. Of 312 utilities surveyed in 1978, 20 percent did not chlorinate until after sedimentation or filtration.[20] Some states

"Disinfection, Water Quality Control and Safety Practices of the Water Quality Industry in 1978 in the United States," *JAWWA*, Vol. 75 (1983), p 52.

lowered pH to 8.0, and THM levels in the distribution system were reduced by 36 to 60 percent. At Daytona Beach, Florida, USEPA measured finished water THM levels with and without recarbonation to lower pH and found that finished water THM levels were less if prechlorination was discontinued.[19]

Determining How to Improve Existing Clarification

How to modify existing coagulation/sedimentation or softening processes to enhance organics removal depends on the installation's equipment, the character of the raw water, and the magnitude of the THM problem. In the studies noted above, THM precursors were removed by varying coagulant or lime dose, varying pH, using coagulant aids, and changing the point of chlorination. To determine which chemical modification would improve organics removal, jar tests should be conducted. Ultraviolet absorbance measurements before and after the jar test will indicate the extent of organics removal.

Table 7 suggests jar test and plant test conditions which can be varied in order to determine the most effective way to improve clarification.

In improving coagulation, once the optimum coagulant dose is determined, a cationic polymer (approximately 2 mg/L) or clay (approximately 10 mg/L) plus a cationic polymer (0 to 5 mg/L) could be jar tested. The use of a polymer may widen the pH range corresponding to the optimum coagulant dose for both organics and turbidity removal.

Increasing the lime dose beyond stoichiometric levels and the addition of alum or iron to enhance organics removal during softening could also be evaluated using jar tests, measuring ultraviolet absorbance before and after treatment.

Once the new coagulant and/or lime dose, pH, and effectiveness of coagulant aids have been determined in the lab, they could be tested in the plant. To make a complete evaluation, samples of the raw and finished water should be taken during existing operation and during the test. Both the Inst THM of the raw and finished water and the Term THM of the raw and finished water should be measured. Evaluating the results is discussed in the section *Evaluating Effectiveness of THM Control Methods*, beginning on p 31.

Summary of Improving Existing Treatment

● THM levels have been brought under control at municipal and Army water treatment plants by optimizing existing treatment.

● Coagulant dose, pH, type of organic acids present in the raw water, and where chlorination is done are the most important factors in determining how efficiently conventional treatment removes THM precursors.

● Modifying treatment chemicals and dosages does not require extensive alterations to the physical plant. Optimum doses can be determined by jar testing.

● Lime softening does remove some precursors, and is enhanced when alum or iron are also added.

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[19]Singley, p 24.

Europe and Japan. It reduced organic acid levels by 40 to 60 percent at a lower dose and in a wider pH range than alum.[10]

The use of polymers to enhance organics removal during coagulation/sedimentation has been studied by USEPA. Jar tests were conducted on Mississippi River water with various combinations of coagulants and coagulant aids, using ultraviolet absorbance as an indicator of organics removal. Adding a cationic polymer (2 mg/L) to an alum or ferric sulfate coagulant enhanced removal of organics from raw water when coagulant dose was up to the optimum dose for organics removal.[11] Of a given type of polymer, those of higher molecular weight were superior.[12] Nonionic and anionic polymers used as coagulant aids did not improve organics removal.[13]

One Army installation is using a polymer as a coagulant aid to control THMs. A dose of 8 lb per million gallons (MG) (approximately 1 mg/L) is mixed and fed continuously through a chemical feed pump at the rapid mixers. THM levels prior to using the polymer exceeded the 0.1 mg/L MCL, but were decreased within 1 day of beginning the treatment. Levels are now below 0.1 mg/L. Another benefit of the polymer is improved settling, which removes the need for an additional coagulant aid.

Addition of (10 mg/L) clay to a cationic polymer (the primary coagulant) prevented restabilization of suspended matter, enabling 40 percent organics removal at primary coagulant doses from 5 to 20 parts per million (ppm).[14] Use of both clay (10 mg/L) and a cationic polymer along with the optimum dose of ferric sulfate, also enhanced organics removal. In that case, cationic polymer doses were less than 5 mg/L.[15]

Lime softening removes some organics. Using ultraviolet absorbance as an indicator of organics removal, the USEPA found that lime doses above stoichiometric dose decreased the concentration of organics by 36 percent. When 20 mg/L of alum or iron were also added, the indicator showed that organics removal improved to 64 percent.[16] Other USEPA studies have shown that the range of precursor removal in lime precipitative softening is from 16 to 41 percent.[17]

THM levels in the distribution system were lowered in some cases by decreasing the pH of the water after softening and before chlorination. As mentioned earlier, more THMs are formed at higher pH. In two plants at Columbus, Ohio,[18] recarbonation

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[10]B. A. Dempsey, "The Coagulation of Humic Substances by Means at Aluminum Salts," *JAWWA*, Vol. 76 (1984), p 146.

[11]Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," p 81.

[12]Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," p 50.

[13]Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," p 58.

[14]Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," p 58.

[15]Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," p 58.

[16]Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," p 93.

[17]*Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, p 108.

[18]*Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in Drinking Water*, USEPA Contract No. 68-01-6292 (USEPA, July 1983), p 20.

Table 6

Processes Related to THM Problems and Key O&M Criteria

	Treatment Understanding	Processing Monitoring and Control	Preventive Maintenance	Analytical Capabilities
Chemical Dosage	x	x		x
Coagulation/ Flocculation		x		
Clarification		x		
Filtering	x	x	x	
Softening	x	x	x	x
Disinfection	x	x		

conventional treatment processes removed from 29 to 51 percent of the THM precursors.[6] A USEPA study of a lime softening plant in Daytona Beach, FL, measured 27 to 43 percent reduction in finished water THM levels (compared to chlorinated raw water with no further treatment, depending on where chlorine was added).[7] Optimizing these processes at Army water treatment plants could be considerably less expensive than use of more costly and sophisticated THM control measures.

Optimizing the type of coagulant, the dose, and the pH has been shown to improve removal of organic acids during coagulation and sedimentation. It is not known how organics removal during coagulation occurs, but experimentation has shown that the order of chemical addition and mixing speed and time have no influence on organics removal when conventional coagulants are used.[8] Coagulant dose, pH, and the type of organic acids present are the most important factors determining the efficiency of organics removal.

One set of tests using Mississippi River water showed that an alum dose of 100 mg/L at pH 5 was optimal for achieving a 65 percent reduction in THM levels. At the same pH, a 25 mg/L alum dose yielded 35 percent removal.[9] Another study found that both alum and polyaluminum chloride (PACl) removed THM precursors. PAC1, although more expensive than alum and not commonly used in the United States, has been used in

[6] *Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, p 2.
[7] J. E. Singley, *Minimizing Trihalomethane Formation in a Softening Plant* (MERL, unpublished), p 17.
[8] M. J. Semmens, "Optimizing Coagulation--Adsorption for Haloform and TOC Reduction," USEPA Grant No. GR806373 (MERL, unpublished), p 68.
[9] M. J. Semmens, "Coagulation: Experiences in Organics Removal," *Journal of the American Water Works Association (JAWWA)*, Vol. 72 (1980), p 478.

Table 5

**Summary of USEPA-Identified Methods to Achieve Compliance
With 0.1 mg/L MCL for THMs**

● Improved existing clarification for THM precursor reduction.*

● Movement of the point of chlorination to reduce THM formation and, where necessary, substitute for the use of chlorine as a preoxidant chloramines, chlorine dioxide, or potassium permanganate.*

● Use of chlorine dioxide as an alternate or supplemental disinfectant or oxidant, p 27.*

● Use of chloramines as an alternate or supplemental disinfectant or oxidant, p 29.*

● Use of powdered activated carbon for THM precursor or THM reduction seasonably or intermittently at dosages not to exceed 10 mg/L on an average annual basis.*

Other methods that USEPA said may be considered:

● Introduction of off-line water storage for THM precursor reduction.

● Aeration for THM reduction "where geographically or environmentally appropriate."

● Introduction of clarification where not currently practiced.

● Consideration of alternative sources of raw water.

● Use of ozone as an alternate or supplemental disinfectant or oxidant, p 28.*

_____
*Indicates method is discussed in this report.

Army and municipal treatment plants. Table 6 shows the treatment process these techniques affect. Granular activated carbon (GAC) is also briefly discussed since it is effective in removing THMs.

Improving Existing Clarification

Plant Experience and Experimental Results

Conventional treatment such as turbidity removal and softening has been shown to remove some of the organic acids (THM precursors) and help control THM levels in the finished water. A field study of 10 utilities using Ohio River water determined that the

CHLORINE
CHLORINE

RAPID MIX → FLOCCULATION → SETTLING → FILTRATION → CLEARWELL STORAGE → DISTRIBUTION SYSTEM

PROCESS FLOW DIAGRAM – ORIGINAL CONDITION

LEGEND

INSTANTANEOUS THM CONCENTRATION

THM FORMATION POTENTIAL

+ TERMINAL THM CONCENTRATION
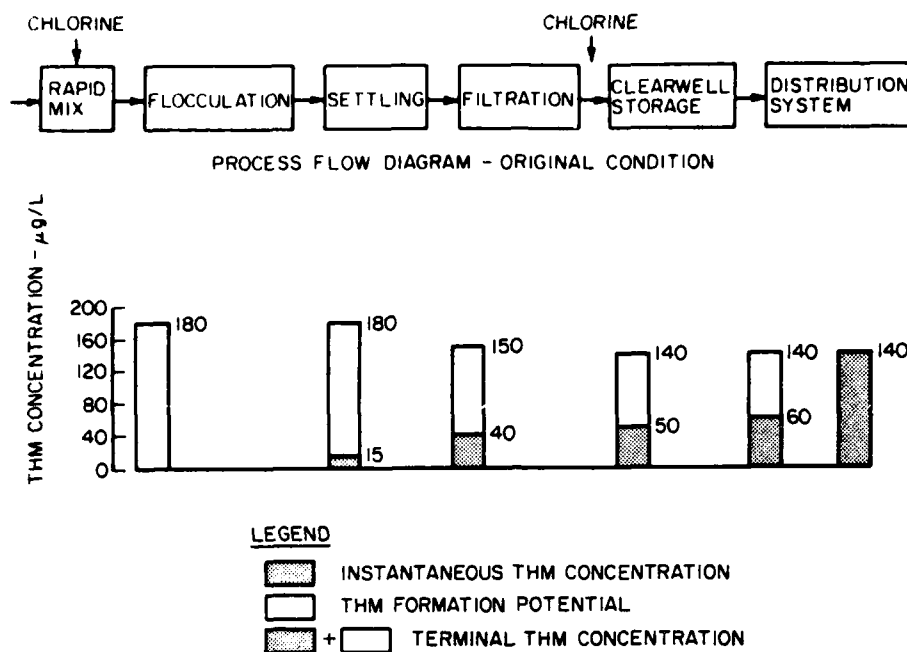
(The maximum contaminant level for THMs is 100 µg/ℓ or 0.1 mg/ℓ)

Figure 1. THM levels through the water treatment plant.

precursors which gradually react to form THMs. Consumers close to the treatment plant would be exposed to lower Inst THM levels than those further out in the distribution system. Inst THM (those already present) are of interest when studying THM levels reaching the consumer, since this is how compliance with the USEPA regulation is determined. In the water treatment plant, it is important to look at both Inst THM and Term THM (THMs already present plus those which could be formed).

Control of THMs

To control THMs in drinking water, THM formation must be prevented or inhibited. This can be done by applying less chlorine, by removing organic acids (THM precursors) which could react to form THMs, or by preventing or inhibiting the reaction between chlorine and organic acids.

In February 1983, the USEPA identified five methods representing the "best technology treatment techniques or other means generally available" to achieve compliance with the 0.1 mg/L limit for THMs in drinking water.[5] These methods and four others that USEPA said may also be considered are summarized in Table 5 and discussed in the following sections. Improving existing clarification to remove precursors, substituting other preoxidants, and chloramination are the most promising methods for Army installations, since they involve conventional treatment processes that have been practiced at

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[5] National Interim Primary Drinking Water Regulations.

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4 TRIHALOMETHANES

The presence of THMs in drinking water has been of concern since about the mid-1970s. Their human health effects can include central nervous system depression, toxicity to the liver and kidneys, and possibly cancer. Drinking water may provide up to 90 percent of the human daily intake of chloroform, a trihalogen that has caused cancer in animals.[3] Because of these concerns and the evidence that THMs are formed as a result of disinfection practices in water treatment plants, the USEPA amended the National Interim Primary Drinking Water Regulations in 1979 to include a Maximum Contaminant Level (MCL) of 0.1 mg/L for total THMs.[4]

How THMs Are Formed

THMs are created when free chlorine reacts with organic acids (humic or fulvic acids) naturally present in the raw water. The chemical makeup of THMs can vary, but they always contain carbon and hydrogen plus chlorine, bromine, and/or iodine from the halogen group of elements. More THMs are formed at a higher temperature, at higher pH, and if the raw water has a high concentration of algae which produce organic acids. Much is still to be learned about how conditions in the treatment plant and presence of other chemicals in the water influence THM formation.

THMs in water may be expressed in three forms:

1. Inst THM (Instantaneous THMs), the amount of THMs existing in the water at a given point in time. This measured value is used for determining compliance with the MCL.

2. THMFP (THM Formation Potential), the amount of THMs which *could* be formed when organic acids in the raw water (precursors) react with free available chlorine (either in the plant or in the distribution system). THMFP represents the amount of precursors in the water before chlorine is added. If no Inst THM are present in the raw water, all the THM is THMFP.

3. Term THM (Terminal THMs), representing the total amount of THMs existing now plus those which could be created by precursors reacting with free available chlorine.

Inst THM and Term THM can be measured. For Term THM, the sample must be chlorinated at the same dose used at the plant and stored for 7 days under the same temperature and pH conditions as in the plant before measuring THMs present. Precursors, represented by THMFP, are calculated by subtracting Inst THM from Term THM.

Figure 1 shows how Inst THM (shaded portion) typically increases as raw water travels through the plant and the distribution system until reaching the Term THM level. The THMFP portion decreases over time because this represents the acid

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[3] *Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, Technical Report PB 82-163197 (Municipal Environmental Research Laboratory [MERL], 1981), p 2.

[4] National Interim Primary Drinking Water Regulations, Amendment Trihalomethanes, 48 Code of Federal Regulations (FR) 8406, February 28, 1983.

● Preventive Maintenance--Is there an up-to-date preventive maintenance program, including a schedule and checklist for routine inspections, lubrication, calibration, replacement, spare parts list, etc.? Do plant personnel follow the program?

● Analytical Capabilities--Are personnel familiar with proper analytical techniques? Is such guidance available? Does the lab have a quality control program and follow it?

After filling out the table, the ratings should be summed on the last line; the column with the highest total represents the O&M criterion where most improvement is needed.

Action should be taken to correct the problems that surface. For example, if Treatment Understanding receives the highest rating, treatment plant operators could be given more insight into the function and importance of various treatment steps (why chemical dosage is important in removing THM precursors, or why filters are operated a certain way, etc.). Again, the following chapters on specific problem areas should be helpful in suggesting approaches to a problem.

Table 4

Worksheet for Evaluating O&M for Water Treatment Plant Processes

| | O&M Criteria to Be Evaluated* for Each Process | | | | |
Process	Staff Adequacy	Treatment Understanding	Process Monitoring & Control	Preventive Maintenance	Analytical Capabilities
Chemical Dosage					
Coagulation/ Flocculation					
Clarification					
Filtering					
Softening					
Disinfection					
Stabilization					
Membrane (RO)					
Ion Exchange					
Totals					

*Assign ratings as follows:
0 = No problem or not applicable
1 = Minimum problem
2 = Moderate problem
3 = Most problem

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Table 3

Relating Water Treatment Plant Problems to Processes and O&M Criteria

Process	Problem That Could Be Affected by Imperfection in Process								Most Important O&M Criteria for Process
	THMs	Corrosion	Sludge Handling	Iron & Mang.	Trace Organics*	High Salinity	High Fluorides	High Nitrates	
Chemical Dosage	x	x	xx**	x	x				B,C,E
Coagulation/Flocculation	x	x	x	xx	x		x		C
Clarification	x		x		x				C
Filtering	x		x	x	x				B,C,D
Softening	x	x	x	x	x		x		B,C,D,E
Disinfection	xx			x	x				B,C
Stabilization		xx		x	x				B,C,E
Membrane (Reverse Osmosis)					xx	xx	xx	xx	C,D
Ion Exchange	x				xx	x	x	xx	B,C

A Staff Adequacy
B Treatment Understanding
C Process Monitoring & Control
D Preventive Maintenance
E Analytical Capabilities

*Strategies for Controlling and Removing Trace Organic Compounds from Potable Water Supplies at Fixed Army Installations, TR N-85/11 (USA-CERL, Draft).

**Double 'x' indicates processes that are particularly related to the problem at the head of the column.

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3 RELATING TREATMENT PROBLEMS TO PROCESSES AND OPERATION AND MAINTENANCE CRITERIA

Tables 3 and 4 serve as a starting point for personnel responsible for the design and operation of water treatment plants to evaluate how well various processes in existing plants are functioning, to identify operation and maintenance (O&M) weaknesses, and to relate treatment processes and O&M criteria to treatment problems.

Relating Problems to Processes

Table 3 identifies water treatment plant problems that could be caused or influenced by treatment processes. Particular attention should be given to processes such as coagulation that can influence a number of problems.

Certain problems, such as THMs and sludge handling, are influenced by a number of treatment processes. The most appropriate corrective measures may be harder to determine in these cases, since several treatment steps need to be evaluated to find a solution. However, this can also mean that more options for corrective treatment are available, or that the problem might be controlled by a combination of changes to more than one process.

The common problems at Army plants and the related treatment processes are discussed in detail in the following chapters. Table 3 should be used along with the information in the chapters to help solve treatment problems.

Table 3 also relates the most important O&M criteria to treatment processes. In trying to improve a certain process, those O&M criteria should be reviewed first. For example, feeding the correct chemical dosage depends on treatment understanding, process monitoring and control, and analytical capabilities. Further evaluation of a water treatment plant, using Table 4, may reveal other important O&M criteria that could be improved.

Evaluating O&M Criteria for Water Treatment Plant Processes

Table 4 can be used to rank O&M problems for a given treatment process. The O&M criteria listed in the table are elaborated as follows:

● Staff Adequacy--Are the level of staffing, supervision, productivity, familiarity with the equipment operation, motivation, morale, level of training adequate?

● Treatment Understanding--Do operators understand how the treatment process works (e.g., how to determine optimum dosage) and why certain practices are used? Do they understand why the process works or fails? Is appropriate technical guidance available to gain the understanding?

● Process Monitoring and Control--Do personnel monitor and record important parameters of the process (e.g., pH, temperature, flow)? Can they interpret the monitoring data and respond to changes/problems? Are they able to troubleshoot in the event of problems?

Table 1

Distribution in Treatment Facility Age and Size

Treatment Capacity (mgd)	No. Installations	% of 27 Installations*
Less than 1	2	7.4
1-5	20	74.0
5-10	7	26.0
More than 10	1	3.7

Treatment Plant Age (Yrs)	No. Installations	% of 23 Installations*
Less than 10	2	8.7
10-20	2	8.7
20-40	4	17.4
More than 40	18	78.2

*Three installations have more than one water treatment plant, so total is more than 100 percent.

Table 2

Percentage of Survey Installations With Selected Water Treatment Problems

Water Treatment Problem	Installation Percentage
High iron and manganese	13.6
Sludge disposal	11.4
THMs (currently or in the past)	9.0
High fluorides	6.8
High salinity	4.5
High nitrates	4.4

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2 ARMY WATER TREATMENT FACILITIES

Information was obtained on the water sources and treatment methods at 93 Army installations. The information was collected from the Redbook[2] and from telephone conversations with installation personnel. Of the 93 installations, 24.7 percent have surface water supplies, 40.9 percent have groundwater supplies, and 30.1 percent purchase water from a nearby municipality. Thirteen percent (not including those installations that purchase water) have both surface and groundwater supplies, which means they may have to treat two water supplies having very different characteristics.

Telephone conversations with personnel at 44 installations provided characteristics of the water treatment types used and water treatment problems. Nineteen, or 43 percent, currently either chlorinate or fluoridate their water with no other treatment. The remaining 25, or 57 percent, have facilities which provide other treatment, such as coagulation, softening, or stabilization.

Installations with water treatment facilities (either chlorination/ fluoridation only or more comprehensive treatment) were asked about the age and capacity of their facilities. Facility ages and capacities were obtained from 23 and 27 installations, respectively (three installations have more than one treatment facility). Over three-fourths (78.2 percent) of the installations surveyed have treatment plants more than 40 years old. About three-fourths are between 1 and 5 million gallons per day (mgd)* in size. Table 1 shows the distribution in treatment facility age and size.

Of the 25 installations with more than just chlorination/fluoridation, 80 percent use coagulation/sedimentation, 36 percent soften the water, and 36 percent treat the water for corrosion control. Sixty-eight percent indicated they had corrosion problems. Two of the 44 installations surveyed have reverse osmosis units, 13.6 percent stated that high iron and manganese were a problem, and 11.4 percent noted that information on sludge disposal would be desirable. Table 2 shows other problem areas, along with the percentage of the 44 installations reporting them.

The traditional treatment practices of turbidity removal, softening, and corrosion control represent a large area where existing treatment could be made more efficient by improving operation and applying new treatment techniques. The problems of corrosion, high iron and manganese, sludge handling, and inorganic compounds such as fluorides and nitrates have been of greater concern because of the USEPA drinking water regulations. They too can be addressed by altering existing treatment procedures and/or employing new treatment techniques. Chapter 3 describes how this could be done.

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[2]*Facilities Engineering Annual Summary of Operations, FY81* (Office of the Chief of Engineers, 1981).

*Metric conversion factors are provided on p 119.

Approach

Information was gathered from Army installations, Major Command (MACOM) personnel, the Facilities Engineering and Support Agency (FESA), and the Office of the Surgeon General to identify treatment processes that are inadequate for meeting regulatory requirements. New technologies to replace those processes were then investigated for possible application to Army facilities. A systematic approach was developed that installation personnel could use to relate operational problems to water treatment processes and then identify key design, operation, and maintenance criteria for improving those problems.

The U.S. Environmental Protection Agency (USEPA) recently developed the Composite Correction Program (CCP), a methodology for improving performance of wastewater treatment plants.[1] This approach seeks to maximize the benefits gained by upgrading existing wastewater water treatment operations. This report uses the same approach as the CCP, but is oriented toward Army water treatment plants.

Mode of Technology Transfer

It is recommended that the information in this report form the basis for one or more Engineer Technical Notes. This information may also impact Technical Manual (TM) 5-660, *Operation of Water Supply and Treatment Facilities at Fixed Army Installations*, and TM 5-813-3, *Water Treatment*.

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[1]*Improving POTW Performance Using the Composite Correction Program*, EPA-625/6-84-008 Handbook (U.S. Environmental Protection Agency [USEPA], 1984).

require chlorination prior to filtration, so installations should check state regulations before eliminating chlorination ahead of the filters. A USEPA study of nine utilities showed that total THM concentration of finished water was reduced up to 80 percent by delaying chlorination.[21] A 1979 Army Environmental Hygiene Agency (AEHA) study at Fort Monroe demonstrated that eliminating prechlorination reduced total THMs in finished water 50 percent.[22] The Louisville, Kentucky Water Company reduced average total chlorine consumption by about 80 percent as a result of moving the chlorination step to the sedimentation basin outlet, prior to the softener. Chlorine dosage had been 120 to 140 lb/MG and 12 to 15 lb/MG for pre- and postchlorination, respectively. With the new arrangement, only 20 lb/MG are used before the softener and 6 lb/MG after filtration. (Ammonia is also added at both points to create a combined residual.) THM levels had exceeded the MCL, but are now less than 20 percent of the MCL.[23]

At the Patuxent (surface water) plant of the Washington Suburban Sanitary Commission, chlorine is added only once, before the filters, at a dose of 3.25 to 3.5 mg/L to create a finished water with a total residual of 1.5 to 1.6 mg/L. (Water to the filters has 6 to 6.5 pH and is adjusted after filtration.) Previously, when raw water was chlorinated, the chlorine dose was 4 to 5 mg/L and THM levels approached the MCL. Now THM levels are 20 to 25 percent of the MCL.[24] No problems have been reported with sludge going septic. The raw water is chlorinated for 4 hours once or twice a week to prevent bacteria and algae growth in the sludge or setting basins, particularly in summer. At the Commission's Potomac plant, chlorine is applied to filter effluent only. This has kept THM levels under control and reduced chlorine consumption by about 40 percent.[25]

The AEHA conducted tests at one Army installation to determine the effects of eliminating prechlorination on THM precursor removal by the existing treatment processes.[26] When prechlorination was stopped and chlorine was only applied to filtered, pH-adjusted water, THM precursor removal by the filters was 73 percent, compared to 20 percent when the water was both pre- and postchlorinated. It is also interesting that THM precursor removal during coagulation/sedimentation was the same, 36 percent, whether or not the water was prechlorinated. USEPA studies confirm the most benefit in controlling THMs is when chlorine is applied after the filters.[27]

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[21] *Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in Drinking Water*, p 12.

[22] *Water Quality Engineering Special Study (Trihalomethanes and Other Organics in Drinking Water)*, U.S. Army Environmental Hygiene Agency [USAEHA] No. 31-61-0139-80, Ft. Monroe, VA (USAEHA, 1979).

[23] D. Duke, Superintendent of Purification Works, Louisville Water Company, Louisville, KY, Personal Communication, May 7, 1984.

[24] Frank Jamerson, Washington Suburban Sanitary Commission, Personal Communication, May 3, 1984.

[25] T. Beecham, Washington Suburban Sanitary Commission, Personal Communication, May 27, 1984.

[26] R. D. Miller, *Approaches for Trihalomethane Reduction in Drinking Water Using Existing Facilities* (USAEHA, unpublished).

[27] *Treatment Techniques for Controlling Trihalmethanes in Drinking Water*, p 108.

Factors to Consider

Consider the following when determining if the point of chlorination should be moved to a later step in the treatment process:

● Delaying chlorination can reduce THM formation because there is less chance for chlorine to react with organic acids. The greatest benefit in THM control is when chlorination is delayed as long as possible in the treatment process (e.g., after filtration).

● Delaying chlorination has been practiced successfully at municipal and Army water treatment plants.

● Since chlorine is applied to cleaner water, a smaller dose is required and total chlorine consumption can be drastically reduced.

● Occasional prechlorination may be needed, depending on the raw water quality, weather conditions, and other pretreatment steps. Bacteria and algae growth in the plant (settling basins and filters) should be monitored to determine this.

Use of Alternate or Supplemental Disinfectants or Oxidants

Where prechlorination is done for oxidation to remove iron and/or manganese, an alternate oxidizing agent such as chlorine dioxide, potassium permanganate, or ozone may be necessary to control THM levels. A chlorine substitute may also be needed as a primary disinfectant. These alternatives will be discussed briefly.

Chlorine Dioxide

Chlorine dioxide is considered both an oxidizing agent and a disinfectant. As of 1977, 84 U.S. water treatment plants and 495 European plants were using it.[28] In pretreatment, it oxidizes soluble iron and manganese and controls tastes and odors caused by phenols and algae blooms. It is used more widely in Europe for final disinfection.[29] USEPA reported only one utility[30] serving more than 75,000 people in the United States where permanent facility modifications had been made to feed chlorine dioxide, and only two others where facilities are being added.

Chlorine dioxide is a more powerful disinfectant than chlorine in the pH range 7 to 10,[31] and THM formation is decreased. THM concentration in the distribution system at Mobile, Alabama, was over 50 percent lower than with disinfection with free chlorine.[32]

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[28]*Trihalomethanes in Drinking Water: Sampling, Analysis, Monitoring and Compliance,* EPA 570/9-83-002 (USEPA, 1983), p 32.

[29]*Trihalomethanes in Drinking Water: Sampling, Analysis, Monitoring and Compliance,* p 32.

[30]*Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in Drinking Water,* p 18.

[31]*Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations,* EPA-600/8-77-005 (USEPA, 1978), p 50.

[32]*Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in Drinking Water,* p 19.

Because it is very unstable, chlorine dioxide is generated on site, usually by adding hydrochloric acid or aqueous chlorine to aqueous sodium chlorite. Chlorite and chlorate ions may also form during this process.[33] Since these ions may have detrimental health effects, USEPA recommends that total residual oxidants (chlorine dioxide, chlorite, and chlorate) in the distribution system be limited to 1.0 mg/L.[34] Techniques for measuring total residual oxidants (including chlorate) are being developed by USEPA. In the interim, Methods 330.6 or 330.7, available from the Environmental Monitoring and Support Laboratory, Cincinnati, OH, may be used. Chlorine dioxide and chlorite residual may be measured by 411C in Standard Methods (15th ed.). Other health concerns are the compounds formed when chlorine dioxide reacts with humic acids or synthetic organic chemicals; the nature and impact of these byproducts are under study.

Potassium Permanganate

Potassium permanganate, used widely to oxidize iron and manganese and organic matter, is useful for taste and odor control. It should be added early in treatment to allow enough time for it to react and to prevent water from passing out of the clarifier while the purple color is still present. It should be fed before powdered activated carbon, if used, because the carbon causes the permanganate to be used up more rapidly. Typical dosage is in the range of 0.5 to 2.5 mg/L, used with a primary coagulant. The optimum dose should be determined by jar tests at various pH levels. If prechlorination is discontinued, potassium permanganate may provide the additional oxidizing power needed in pretreatment to remove organic matter so that chlorine dosages can be reduced, in turn controlling THM formation. The cost of potassium permanganate should be evaluated against the savings in reduced chlorine use and the benefits of THM reduction.

Ozone

Ozone is a very powerful oxidant and is widely used in Europe, where raw waters are poor quality. It acts more quickly as a bactericidal agent than chlorine and is effective against some viruses.[35] It does not combine with organic acids to produce THMs. Ozone has been used to assist in removal of iron, manganese, and organics, and USEPA and others[36] have done some experimental work to demonstrate that ozone pretreatment reduces THM levels. Actual operating experience and measurement of THM levels in U.S. water treatment plants is limited, however.

Ozone's disadvantage is that it must be produced onsite by discharging high voltage (5000 to 30,000 V) between electrodes separated by air, requiring a high initial investment for the equipment. Capital cost is about two-thirds greater than for chloramines or chlorine dioxide treatment. Also, since ozone cannot provide enough residual in the distribution system, another disinfectant is required. Part of a large settling basin can be modified for use as an ozone contact chamber.[37] The advantages of ozone pretreatment have to be weighed against the cost of purchasing and operating an ozone generator.

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[33]*Manual of Treatment Techniques for Meeting the Interim Primary Drinking Water Regulations*, p 50.

[34]*Trihalomethanes in Drinking Water: Sampling, Analysis, Monitoring and Compliance*, p 32.

[35]W. J. Weber, *Physiochemical Processes for Water Quality Control* (Wiley Interscience, 1972), pp 447-448.

[36]*Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, p 181.

[37]P. W. Prendiville, "Upgrading Water Filtration Plants," *Civil Engineering*, Vol. 53 (1983), p 64.

Chloramination for Supplemental Disinfection

When chlorine is added to water, the hypochlorous acid (HOCl) formed reacts with ammonia (NH$_3$) to form the chloramines monochloramine and dichloramine. Although not as powerful disinfecting agents as hypochlorous acid, the chloramines do provide a residual in the distribution system and also suppress formation of THMs. The reactions to form chloramines are:

$$Cl_2 + H_2O \rightarrow HOCl + H^+ + Cl^-$$

$$HOCl + NH_3 \rightarrow NH_2Cl + H_2O$$

monochloramine

$$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O$$
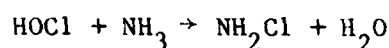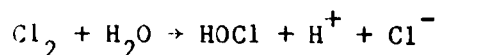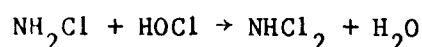
dichloramine

When chloramination is practiced, chlorine and ammonia are added in water treatment and enough reaction time is allowed for the chloramines to form. The pH, temperature, and chlorine and ammonia concentrations influence the reactions. If pH is 4.4 or less, nitrogen trichloride, which is malodorous and a poor disinfectant, is formed.

Ammonia can be added as ammonium sulfate (25 percent ammonia) with a dry chemical feed system, as anhydrous ammonia (refrigeration gas) fed in solution or diffused in gaseous form, or as aqua ammonia (food grade) diffused in liquid form. The choice depends on how easily the facilities at the treatment plant can be adapted to accommodate ammonia feed.

The ammonia dose is such that the ratio of chlorine to ammonia is 3:1 to 5:1 and a combined chlorine residual of 1 to 2 mg/L is achieved.

Chloramines do not react with organic acids to form THMs as free chlorine does. If chlorination occurs early in the treatment process, THMs can still form in the plant, but further THM formation will be suppressed after NH$_3$ is added and chloramines are produced. On the other hand, early chlorination provides free available chlorine to protect against bacterial and algal growth.

Plant Experience

Chloramination has enabled some utilities to significantly reduce THM levels in the distribution system. In Huron, South Dakota, chlorine and ammonium sulfate have been added at the recarbonation basin since 1979 (following separate treatment steps with alum, permanganate, and powdered activated carbon). About a 1 hour contact time is provided to develop 1 mg/L combined chlorine residual before filtration. Chlorine is again added to the filter effluent before water enters a storage reservoir (although this second dose may not be necessary). Total chlorine residual of finished water is 1.5 to 3 mg/L.[38] THM levels as high as 0.3 mg/L had been measured in the distribution system; after chloramination, THM levels were reduced an average of 75 percent.[39]

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[38]H. Scheele, Chief Operator, Water Treatment Plant, Huron, SD, Personal Communication, May 7, 1984.

[39]*Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, p 181.

The Louisville, Kentucky, Water Company reduced THM levels from a maximum of over 0.2 mg/L to below 0.02 mg/L after switching to chloramination. Prechlorination (20 lb/MG) is done after the coagulation/sedimentation step to a free chlorine residual of 2 mg/L. After 15 minutes of contact time as water flows through a tunnel, 5 to 6 lb/MG of liquid ammonia is added to form monochloramine (pH 6.8 to 7.0). After softening and filtration, 6 lb/MG of chlorine and 1.6 lb/MG of liquid ammonia are added to produce a combined chlorine residual of 1.5 mg/L in the distribution system.[40] The system is flushed when standard plate counts of bacteria at various points in the distribution system exceed predetermined levels. This program controls both THMs and bacteria.

At one Army installation, prechlorination of raw water to 1.5 to 2 mg/L free available chlorine provides a residual of 0.1 mg/L through the sedimentation basin to prevent algae growth. After filtration and pH adjustment, chlorine and ammonia are added in a ratio of about 5:1 to provide a total residual of 2.6 mg/L in the finished water. The anhydrous ammonia is added just before the chlorine to minimize additional THM formation. This practice has brought THMs well below the MCL. A flushing program keeps lines free of bacteria and algae, and bacteriological samples are taken regularly. (The flushing program is necessary because of high algae levels in the raw water at this installation.)

Primary Considerations

The primary considerations in chloramination are:

● Chloramines act as disinfectants but work much more slowly than free chlorine. They are not as effective in destroying viruses, but provide a stable residual in the distribution system.

● Chloramines do not react with organics to form THMs. They have effectively controlled THMs in Army and municipal water treatment plants.

● Chlorine:ammonia dosage ratio of 3:1 to 5:1 with adequate contact time should be maintained if chloramines are used for disinfection.

● A combined chlorine residual in the distribution system of at least 0.5 mg/L should be maintained.

● Periodic bacteriological sampling and pipe flushing are recommended to insure bacteria levels are controlled.

● If prechlorination has been discontinued, it may have to be resumed intermittently to control bacteria and algae within the plant.

Powdered Activated Carbon (PAC)

Attempts to remove THM precursors with PAC have had varied results. PAC is added before the rapid mix, but the dosage required to remove any significant THM precursors is usually too high to be cost effective.[41] Also, USEPA regulations restrict

[40] D. Duke, Personal Communication, May 7, 1984.
[41] *Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, p 138.

average annual dosages to 10 ppm,[42] so the dosages should be adjusted seasonally or as needed. Because so many factors influence precursor removal, jar tests should be conducted to determine the appropriate dosage.

Granular Activated Carbon (GAC)

Although USEPA did not identify GAC as a method for meeting THM regulations, experimental work now under way may lead to its wider use. (GAC is already used for taste and odor removal.) Some water treatment plants, such as the one in Little Falls, NJ, have effectively controlled THM levels in the distribution system by replacing a portion of the sand filter with GAC.[43]

Factors under study regarding the design and performance of GAC treatment are: raw water quality (type of acids or THMs present), bed density and depth, approach velocity (gal/min-sq ft), and days of operation until exhaustion. Some studies have shown that frequent bed replacement is necessary to achieve consistently acceptable THM removal rates.[44]

The length of time to bed exhaustion has been found to be longer if the bromine portion of the total THM is higher.[45] Microbial activity within the filter bed may also help remove THMs.[46] Some USEPA studies have shown that GAC may be more appropriate for removing THM precursors than for removing THMs, especially when used with other THM control techniques.[47]

Evaluating the Effectiveness of THM Control Methods

To determine how well the existing treatment facilities control THMs, or to evaluate how effectively modified treatment reduces THM levels in finished water, Inst THM and Term THM levels should be compared for raw and finished waters with existing and modified treatments. This sampling is separate from the monitoring and reporting required by USEPA regulations.

The format shown in Table 8 can be used to compare the THM control effectiveness of existing versus modified treatments. In both cases the Inst THM of the raw water will probably be zero; the Term THM levels may differ, however, due to a change in the amount of organics in the water entering the plant.

In both existing and modified treatments, the Term THM of finished water may be lower than that of raw water because THM precursors may be removed in the plant. The Inst THM of the finished water represents how much THM was formed within the plant.

[42] Technologies and Costs for the Removal of Trihalomethanes from Drinking Water (USEPA, December 1982), p 8.
[43] Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in Drinking Water, p 21.
[44] Trihalomethanes in Drinking Water: Sampling, Analysis, Monitoring and Compliance, p 33.
[45] Treatment Techniques for Controlling Trihalomethanes in Drinking Water, p 138.
[46] Trihalomethanes in Drinking Water: Sampling, Analysis, Monitoring & Compliance, p 33.
[47] Treatment Techniques for Controlling Trihalomethanes in Drinking Water, p 138.

Table 8

Evaluating Treatment Modifications to Control THM Levels
(to be completed by installation personnel)

	Raw Water		Finished Water		Term THM-finished/
	Inst THM	Term THM	Inst THM	Term THM	Term THM-Raw
	(A)		(B)		(B)/(A)
Existing Treatment					
Modified Treatment					

The objective is to make sure the Inst and Term THM levels of the finished water are lower with modified treatment. However, a direct comparison of raw versus finished water Term THM or Inst THM is not enough. To evaluate whether the modified treatment is controlling THMs more effectively, take the ratio of the Term THM of the finished over the Term THM of raw water (B/A) as shown in the far right column of Table 8. Do this for both existing and modified treatment. A low ratio indicates that THMs and/or THM precursors are being removed during treatment. If the ratio B/A with modified treatment is lower, then it controls THMs more effectively.

Cost Comparison of Disinfection Alternatives

Table 9 gives 1983 cost estimates for various disinfection alternatives. The costs given for chlorination could be used as a baseline for comparison, or current installation chemical and operating costs, if known, could be used for existing disinfection by chlorination. The estimates for chlorination, chloramination, and chlorine dioxide are given for two cases: where a chlorine feed system exists and only facilities for treatment with the new chemical are needed (case A), and where chlorination and new chemical feed systems are required (case B). The estimates for ozonation are based on 1980 USEPA estimates but have been projected (by multiplying by the average ratios of the 1983 and 1980 Construction Cost Indexes and the Producer Price Index) to 1983 for comparison.

USEPA cost estimates of increased alum and polymer doses needed to meet the MCL are given in Table 10. Cost estimates for various average annual dosages of PAC are shown in Table 11. Better estimates could be made by obtaining delivered prices for the chemicals under consideration.

Other than chemical costs, the cost of modifying existing facilities or providing new treatment for THM control will depend on the facilities (piping, chemical storage and feed, etc.) available at the water treatment plant. Table 12 shows other cost factors to consider when evaluating various alternative oxidizing agents, disinfectants, and THM control methods.

Table 9

USEPA Disinfection Treatment Cost Estimates-Cents/1000 Gal*

Case A -Chlorination feed system exists. New feed system for chemicals
in question.
Case B -New chlorine and other chemical feed systems.

	1 mgd		5 mgd		10 mgd	
	A	B	A	B	A	B
Chlorination**						
1 ppm dose	2.8	3.7	0.8	1.1	0.5	0.7
3 ppm dose	3.6	5.2	1.2	1.6	0.9	1.2
6 ppm dose	4.3	6.2	1.7	2.3	1.4	1.8
Chloramination**						
0.75 ppm chlorine dose	4.9	5.8	1.5	1.8	0.9	1.1
1.5 ppm chlorine dose	5.9	6.9	1.8	2.2	1.2	1.5
2.2 ppm chlorine dose	7.2	8.4	2.2	2.7	1.5	1.8
Chlorine Dioxide,+**						
1 ppm dose	5.6	6.6	2.5	2.8	2.0	2.2
3 ppm dose	9.0	10.3	5.6	6.1	4.9	5.2
Ozonation++						
(10 min. contact time)						
1 ppm dose		6.9		3.5		2.3
3 ppm dose		10.4		5.5		4.0

*All costs shown include capital (where new facilities indicated), operating and
maintenance costs, assuming 70% plant capacity, 20 year amortization period, and
8% interest. ENR Construction Cost Index 369.80 (January, 1983) and Producer Price
Index - Finished Goods 283.6 (Jan. 1983). Chlorine costs $300/ton, Ammonia cost
$200/ton. Chlorine:Ammonia ratio 3:1.

**Based on Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in
Drinking Water, EPA Contract 68-01-6292 (USEPA, 1983), pp 98-102.

+Sodium chlorite cost $2000/ton. Contact time, 20 minutes.

++Costs projected from 1980 costs given in *Treatment Techniques for Controlling
Trihalomethanes in Drinking Water*, Technical Report PB 82-163197 (MERL, 1981).

Table 10

Cost of Increased Alum and Polymer Dosages to Meet THM MCL*

	Increased Dosage - mg/L	Cost - ¢/m³ ** (¢/1000 gal)	
Alum	10	0.16	(0.60)
	20	0.32	(1.20)
	30	0.45	(1.70)
	40	0.61	(2.30)
	50	0.77	(2.90)
Polymer	0.2	0.11	(0.40)
	0.4	0.21	(0.80)
	0.6	0.34	(1.30)
	0.8	0.45	(1.70)
	1.0	0.55	(2.10)

*Costs include only the additional chemical cost, not capital facilities or O&M requirements.

**Assumed alum cost $140/ton; assumed polymer cost $2.50/lb.

Sources: *Evaluation of Treatment Effectiveness for Reducing Trihalomethanes in Drinking Water*, EPA Contract No. 68-01-6292 (USEPA, July 1983), p 98-102; *Treatment Techniques for Controlling Trihalomethanes in Drinking Water*, Technical Report PB 82-163197 (MERL, 1981).

Table 11

Cost of Powdered Activated Carbon to Meet THM MCL*

(Costs are in ¢/m³, with ¢/1000 gal shown in parentheses.)

Plant Design Capacity m³/sec (mgd)		Powdered Activated Carbon Feed Capacity - mg/L**					
		5		15		30	
0.438	(1)	2.64	(10.0)	3.09	(11.70)	3.19	(12.10)
0.219	(5)	0.85	(3.20)	1.24	(4.70)	1.29	(4.90)
0.438	(10)	0.61	(2.30)	1.03	(3.90)	1.06	(4.00)
0.657	(15)	0.55	(2.10)	0.95	(3.60)	0.98	(3.70)

*Source: *Evaluation of Treatment Techniques for Reducing Trihalomethanes in Drinking Water*, EPA Contract No. 68-01-6292, (USEPA, July 1983). Average annual dosage is 5 mg/L for the 5 mg/L feed capacity, and 10 mg/L for the 15 and 40 mg/L feed capacities. This is necessary because the regulations restrict average annual dosage to an upper limit of 10 mg/L.

Table 12

Factors to Consider When Evaluating THM Control Methods

	INITIAL COSTS						ONGOING			
	New Chemical Storage, Mixing and Feed Facilities	New Piping	New Injection Facility	New Contact Basin/Bed	Closer Process Monitoring	Energy Costs to Produce	Chemical Cost/Savings	Cost of Bacteriological Control	Possible Change in Quantity of Sludge Generated	Comments
Chloramines	*	*	*		*		*	*	*	Should also do bacteriological sampling. May also use as oxidizing agent.
Chlorine Dioxide	*		*	*	*	*	*			Also use as oxidizing agent.
Improve Existing Clarification							*		*	May increase coagulant dosages.
Move point of chlorination			*	*				*		May need substitute for prechlorination.
Potassium Permanganate	*		*		*		*		*	
PAC	*		*	*			*		*	
GAC				*			*		*	May replace existing filter media. GAC bed replacement costs.
Ozone				*	*	*	*		*	May reduce existing coagulant dosage. Still need residual in distribution system.
Polymer	*						*		*	
Softening							*		*	Cost of extra lime and possibly coagulant.
pH adjustment	*		*				*			Cost of recarbonation or acid.

35

5 COAGULATION, FLOCCULATION, AND CLARIFICATION

With recent concern about contaminants such as THMs, trace organics, and metals in drinking water, coagulation and flocculation have received more attention as important steps in water purification. Recently there have been a number of studies revealing ways these processes could be improved to obtain better water quality using lower dosages.

Coagulation

The primary function of coagulation is removal of impurities that cause turbidity or color. It is defined as the process of "driving the colloidal particles together by chemical means."[48]

Colloids, or fine particulate matter ranging in diameter from 0.001 to 10 microns (10^{-6} to 0.01 mm), are usually clay particles. Figure 2 shows sizes of collodial particles. Color in water may come from colloid-sized particles of iron or manganese or from organic compounds produced from decaying vegetation. Some of the fine matter will not settle out at all, while other sizes of colloids may take a decade to settle only 12 in.[49]

How Coagulants Work

There are four ways coagulants are believed to destabilize colloidal particles, allowing them to settle out. Coagulants usually produce positively charged ions in water, while most colloids are negatively charged. The presence of the coagulant particles can upset the repulsive forces between colloids, allowing them to be driven together. Or, positively charged coagulant particles may be adsorbed onto the surface of the colloids and neutralize the repulsive forces. Some coagulants are polymers, or molecular chains with positive charges along the length. The polymers are adsorbed onto colloidal particles and bridges between the polymer chains cause the particles in suspension to settle. Another way is by the colloidal particles being trapped and swept out of suspension by coagulants such as metal salts that form a precipitate in the water.

Factors Affecting Coagulation

Factors to consider in trying to improve coagulation are:

● Mixing conditions

● Type of coagulant

● Coagulant dose

● pH

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[48] *Water Treatment Plant Design*, New York (AWWA, 1971), p 65.
[49] D. R. Kasper, "Use of Polymers in the Coagulation Process," *AWWA Seminar Proceedings, Use of Organic Polyelectrolytes in Water Treatment*, Las Vegas, NV (June 5, 1983), p 73.

Diameter, meters

10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}

1 Å   1 μm   1 mm

Molecules

PARTICLES

Colloids
(Removed By Coagulation)

Suspended Particles

Bacteria

Algae

Virus
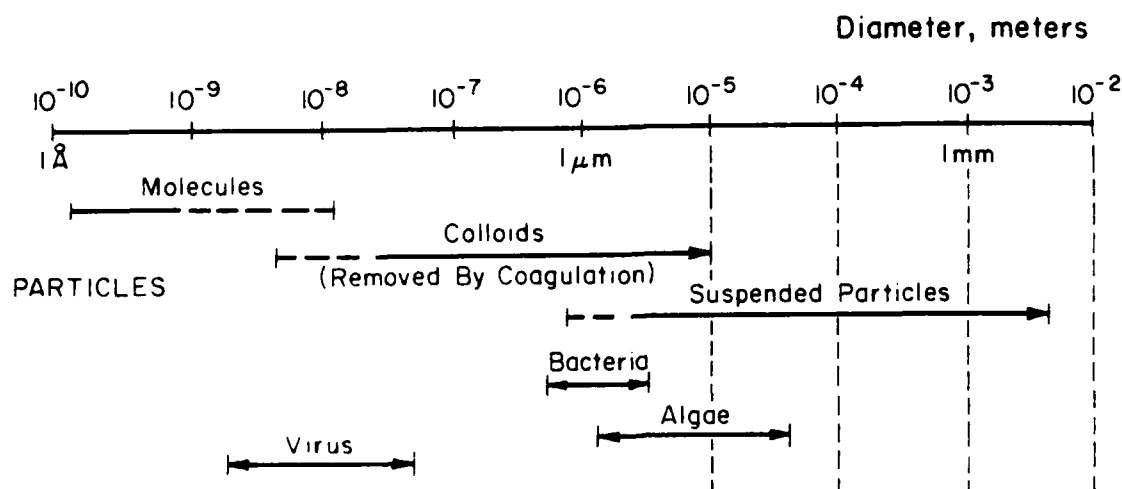
Figure 2. Particle size compared to filter sizes.

- Raw water characteristics (pH, turbidity, and chemical composition)

- Use of coagulant aids.

Treatment understanding, process monitoring and control and analytical capabilities are important O&M criteria for coagulation.

Mixing Conditions. Coagulants should be mixed instantly and thoroughly with the dilution water. This is done at the rapid mixer, sometimes referred to as a flash mixer. Recent tests[50,51] have revealed that poor distribution of the coagulant into the water, insufficient agitation, short circuiting through the mixer, and inadequate mixing time hinder coagulant effectiveness. These deficiencies cause the coagulant to be unevenly mixed in the water, adversely affecting the rate of adsorption onto colloidal particles or rate of precipitation. The result is wasted coagulant and inefficient removal of colloidal material.

The backmixers conventionally used at water treatment plants, such as the one shown in Figure 3, cause some of these problems. More recently, plug flow mixing devices like the simple version shown in Figure 4a have been recognized as more quickly and thoroughly mixing the chemicals. Figure 4b shows a more sophisticated version of a plug flow reactor with chemical injection at points around an orifice plate. Chemicals could also be added by hydraulic eductors or injection pumps or through orifices distributed on a grid across the flow. These types of mixers use five times less energy than mechanical mixers.[52] In-line blenders with variable speed motors for varying flow rates may be considered to improve mixing.

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[50] R. E. Forbes, "Upgrading Water Treatment Plants: An Alternative to New Construction," *JAWWA*, Vol. 72 (1980), pp 254-261.

[51] S. Kawamura, "Consideration on Improving Flocculation," *JAWWA*, Vol. 68 (1976), p 328.

[52] E. Bowers, "New Concepts in Filtration Plant Design & Rehabilitation," *AWWA Seminar Proceedings, Upgrading Water Treatment Plants to Improve Water Quality*, Atlanta, GA (June 15, 1980), p 83.
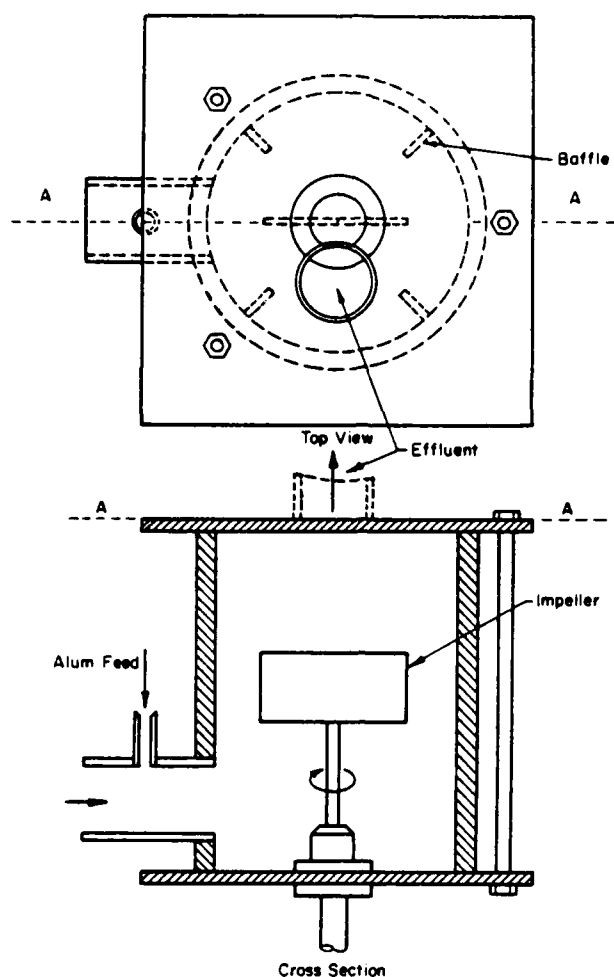
Figure 3. Typical backmixer. (Reprinted from *AWWA Seminar Proceedings, Upgrading Existing Water Treatment Plants*, T. P. Brodeur, "Upgrading Performance Characteristics to Improve Water Quality," by permission. Copyright © 1974, The American Water Works Association.)

Another aspect of mixing coagulants is that coagulant feed should be continuous. If the coagulant solution is pumped by an on-off system or in a manner creating a pulsing effect, the chemicals will not be distributed uniformly to the raw water and coagulation will not be as effective.

Types of Coagulants. Alum is the most common chemical for coagulation.[53] Other metal salts such as sodium aluminate, ferric sulfate, ferrous sulfate, ferric chloride, and magnesium carbonate are also used. Alum, iron salts, and magnesium carbonate lower the alkalinity and produce CO_2 when added to raw water. Although iron salts work over a wider pH range, they are more expensive and more corrosive.[54] Magnesium carbonate is attractive because when used with lime, less sludge is produced and it is more easily dewatered. Furthermore, magnesium carbonate can be recovered from the sludge.

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[53] Kawamura, p 328.
[54] Kawamura, p 328.
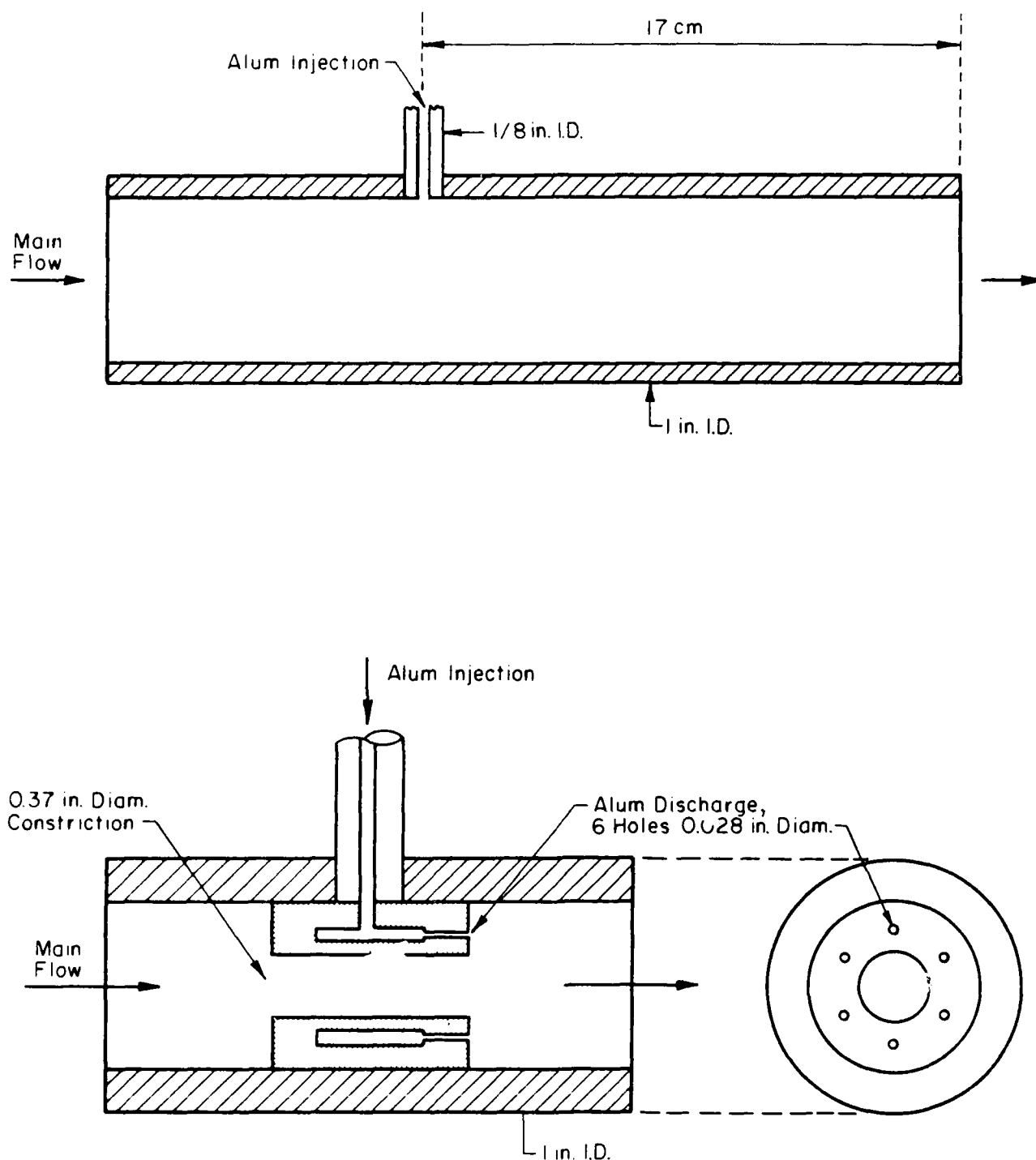
Figure 4. **Plug flow rapid mix units.** (Reprinted from *AWWA Seminar Proceedings Upgrading Existing Water Treatment Plants*, T. P. Brodeur, "Upgrading Performance Characteristics to Improve Water Quality," by permission. Copyright © 1974, The American Water Works Assocation.)

Table 16

Design and Operational Criteria for Flocculation Tanks*

Detention time in basin	30 to 60 minutes
Rotational speed of shaft	2 to 15 rpm
Paddle area	Less than 15 to 20 percent of area in plane of paddle rotation.
Paddle tip speed	Less than 2 ft/sec for weak floc, less than 4 ft/sec for strong floc.
Relative velocity between water and paddle	70 to 80 percent of paddle speed without stators, 100 percent of paddle speed with stators.

*Reprinted from *Process Chemistry for Water and Wastewater Treatment*, by
L. D. Benefield, J. F. Judkins, and B. L. Weand, (Prentice-Hall, Inc., Englewood
Cliffs, NJ, 1982), p 235, courtesy of Marcel Dekker, Inc.

It may be helpful to adjust the size distribution of particles in the water by filling in the "missing" size category of particles in raw water, using a flocculant aid. Colloidal-sized clay, powdered silica, filter backwash, or preformed floc could be added as a "seed" to form better floc. In Europe, tiny sandgrains (a few tenths of a micron in diameter) are used along with polymer to aid settling.[89]

A water treatment plant in Manatee County, Florida, adds 0.2 mg/L of polymer flocculant aid 4 to 5 minutes after floc has formed. Along with other improvements, this has helped expand plant capacity from 12 to 27 mgd while maintaining finished water quality.[90]

Flocculant aids are usually added in the flocculation basin (at the second compartment, if compartmentalized), 2 to 6 minutes after the primary coagulant is added. The tip speed of the blade or paddle in the compartment is recommended to be 0.5 to 1.0 ft/sec.[91] Seven to 10 additional minutes of flocculation are usually allowed before water passes out of the basin.[92]

[89] Benefield, et al., p 330.
[90] T. P. Brodeur, "Upgrading Performance Characteristics to Improve Water Quality," *AWWA Seminar Proceedings, Upgrading Existing Water Treatment Plants*, Boston, MA (June 15-16, 1974), p 55.
[91] Amirtharajah, p 62.
[92] Amirtharajah, p 62.
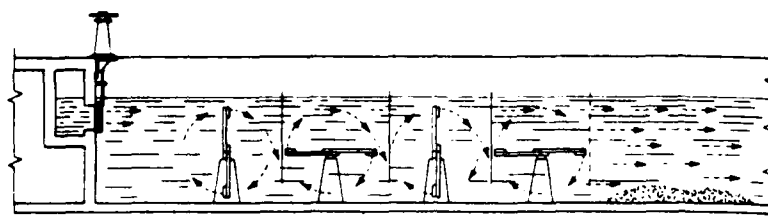
Flocculating equipment A series of paddles placed transversely across the tank
width are arranged to impart a barrel-roll motion to the water.
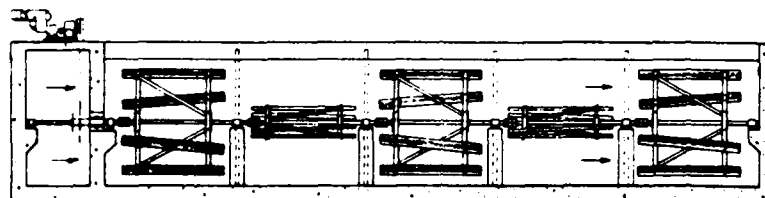
Paddle reel flocculator. The intensity of mixing depends on the area of the paddle
blades and the rotational speed of the shaft. The water flows in the direction of
the drive shaft.

Axial-flow propeller flocculator. This mixing unit is similar to the paddle reel
flocculator.
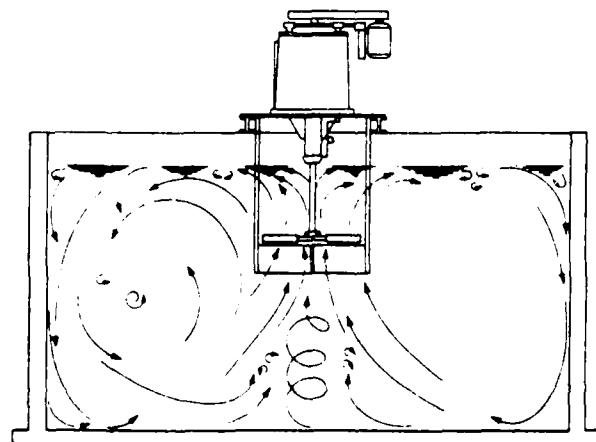
Turbine Flocculator

Figure 9. **Flocculators.** (Reprinted from *Water Quality and Treatment*, by
permission. Copyright © 1971, The American Water Works Association.

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Table 15

Potential Costs and Savings with Coagulant Aids

Costs

- Coagulant Aid Chemical Costs

- Coagulant Aid Storage, Mixing, and Feed Facilities

- Coagulant Aid Feed System O&M

Potential Savings

- Reduced alum dosage

- Reduced caustic used for pH adjustment

- Decreased sludge handling/disposal costs due to less sludge produced, more easily dewatered

- Possible savings incurred by longer filter runs, less backwash water

- Savings due to capital expenses avoided (for example, clarifier or filter overflow rate increased, eliminating need for new equipment)

- Other benefits (better quality effluent, color or taste and odor problems eliminated) resulting in reduced costs of treating those problems separately

basins may have uneven flow and short circuiting, resulting in a portion of the water escaping before floc is fully developed.

When considering installing baffles or weirs in the floc basins, it is worth examining the exit conditions. Submerged weirs or too-small ports leading from the floc basin to the clarifier can create shear forces in the water, causing floc particles to break up and not settle effectively. A submerged perforated baffle would help make flow more uniform as it exits the flocculator basin, but ports should be large enough not to cause jets and shearing.

Particle size distribution is an important factor in flocculation. Colloidal particles range in size from 10^{-3} to 10 microns; to form a floc that settles well, particles from the larger end of the size range (1 to 5 microns) as well as particles less than 1 micron in size should be present.[88]

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[88]Benefield, et al., p 329.
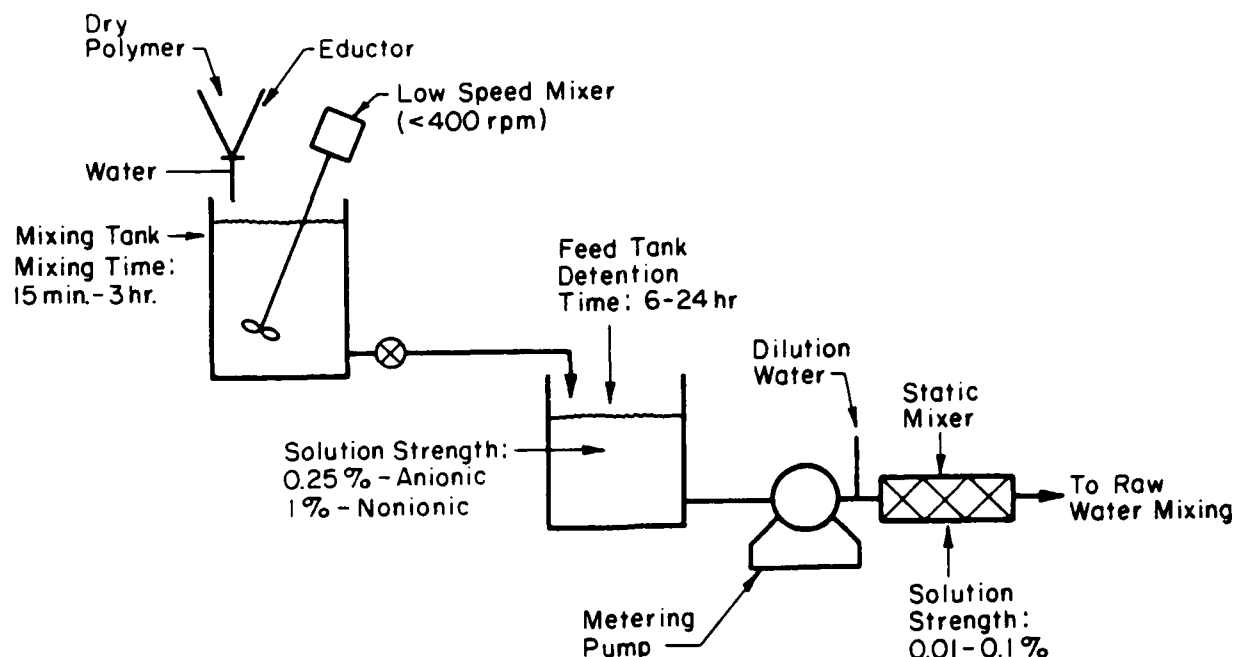
Figure 8. **Typical dry polymer feed system.** (Reprinted from *AWWA Seminar Proceedings, Use of Organic Polyelectrolytes in Water Treatment,* A. Amirtharajah, "System Design for Polymer Use," by permission. Copyright © 1983, The American Water Works Assocation.

The degree of agitation is a function of the power applied to the mechanical mixer, the volume of the basin, and the viscosity of the water. In baffled basins, it is a function of the head loss across the basin, viscosity of the water, and the detention time in the basin. In both cases the velocity gradient is temperature dependent, since water viscosity varies with temperature. In winter, water viscosity increases so that power applied to mechanical mixers could be reduced yet achieve the same degree of agitation.

Too much agitation will break up floc particles. The velocity gradient is reflected in rotational speed of the shaft, relative velocity between water and the paddles, and paddle tip speed. That is why paddle tip speed should be less than 2 ft/sec for a weak floc, whereas a stronger floc can tolerate a paddle tip speed of less than 4 ft/sec. Floc created from an organic polymer coagulant is often stronger than floc produced from an iron or aluminum salt coagulant,[87] so paddle tip speed could be higher.

As seen in Table 16, the detention time in the flocculation basin is much longer than in the rapid mix. A detention time of 30 to 60 minutes is needed to allow growth of large, settleable floc particles. Baffles or weirs may be installed in the floc basin to lengthen detention time if necessary, and to make flow more uniform. Otherwise, floc

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[87]L. D. Benefield, J. F. Judkins, and B. L. Weand, *A Process Chemistry for Water and Wastewater Treatment* (Prentice-Hall, Inc., Engelwood Cliffs, NY, 1982), p 235.

A dry mixing and feeding system may be either semi-batch or automatic. Figure 8 shows a typical dry feed system. The principal components are a wetting device, a slow speed mixing tank (to mix a solution of 1 percent for nonionic and 0.25 percent for anionic polymers), a feed tank (where the solution would be stored less than 24 hours), and metering pump to transfer the solution to a static mixer. In the static mixer it is further diluted to a 0.01 to 0.1 percent solution strength before adding to the water.[83] The wetting device (ahead of the mixer) is important. The most successful types are a hydraulic eductor funnel or a water spray with two drums rotating in opposite directions.[84]

An automatic feed system has the same components as the semi-batch system, but hi/lo level switches on the mixing and feed tanks control the polymer feed. One drawback of this system is that the accuracy of the auger-type dry polymer feed system may only be 2 to 5 percent,[85] which could lead to wasted chemical or feed problems if too much is added. The other drawback of an automatic system is that the valves and eductors must be cleaned and the metering pumps calibrated regularly.

Evaluating Use of Coagulant Aids. Table 15 shows potential costs and benefits to evaluate when considering using coagulant aids.

Flocculation

Once the coagulants are added and the colloidal particles are destabilized, flocculation occurs. Flocculation is the slow mixing process during which the destabilized particles adhere to one another and grow in size, forming a floc. The larger floc particles settle much more readily than the original colloidal particles.

The flocculation basin is located after the rapid mixers, and agitation is much less intense. Mixing should continue uninterrupted from the rapid mix into the flocculation stage, if possible, to improve the quality of settled water.[86]

Flocculating equipment in older plants usually consists of a basin with baffles to gently mix the water and allow floc growth. This design does not allow much control over the degree of mixing or the detention time. Mechanical mixers, using compressed air, paddles, or propellers, provide more control of mixing speed, even if flow rate varies. Motor-driven paddles may rotate transverse to the flow as shown in Figure 9a, or may rotate about a shaft mounted parallel to the flow (Figure 9b). Propellers mounted on a shaft can also do the job (Figure 9c). Figure 9d shows a turbine flocculator, which could be installed in an existing basin.

Criteria for design and operation of mechanically mixed flocculation tanks are shown in Table 16. Flocculation requires the appropriate degree of agitation (the "velocity gradient") and an adequate detention time. Variable speed motors provide much more flexibility in the amount of agitation. Three or more compartments of paddles or propellers in series, each with a different rotational speed, is called tapered mixing. The agitation decreases by about half in each successive compartment. This helps prevent break-up of floc in the last compartment and improves settled water quality.

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[83]Amirtharajah, p 54.
[84]Amirtharajah, p 53.
[85]Amirtharajah, p 54.
[86]Kawamura, p 333.
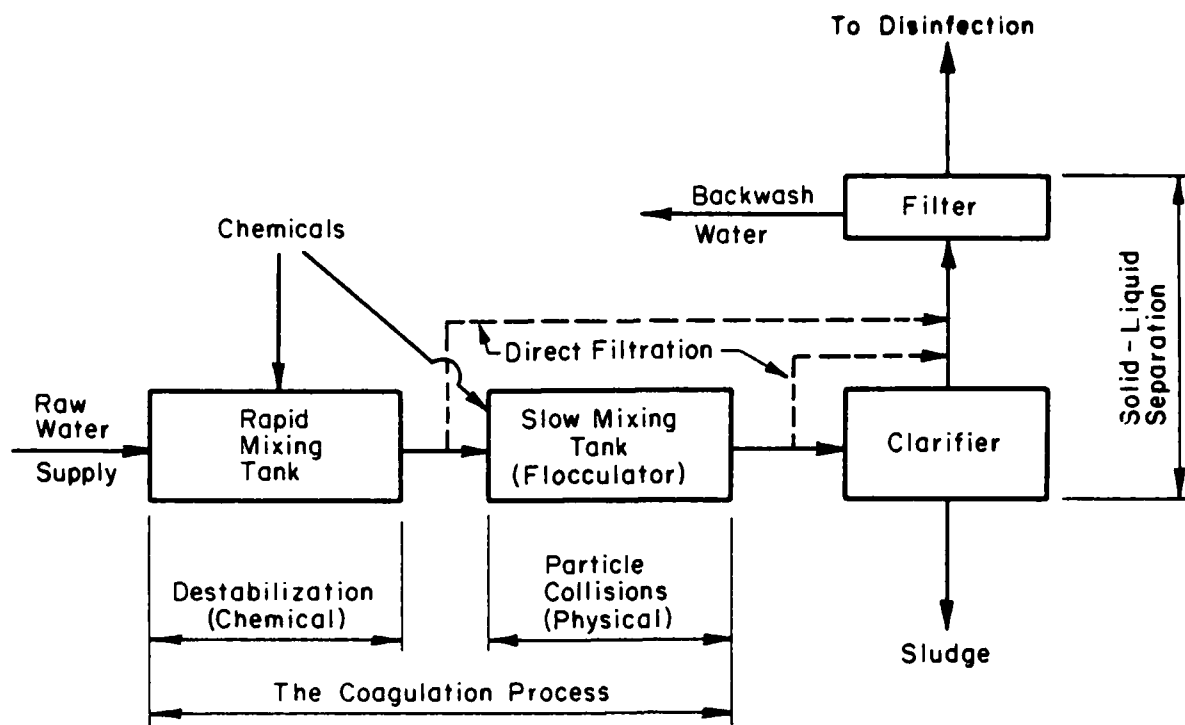
Figure 7. **Process diagram showing where coagulant aid is added.** (Reprinted With permission from R. L. Sanks, *Water Treatment Plant Design*, Ann Arbor Science, 1978.)

Nonionic and anionic coagulant aids usually come in dry form, such as in 25 or 50 lb polyethylene-lined bags or 50 or 100 lb plastic-lined fiber drums. This presents a host of special storage, handling, and feeding considerations. Powdered anionic and nonionic polymers cake easi'v and must be stored in a dry area. If large quantities are to be stored, they must only be exposed to dry air or inert gas. The shelf life of the powdered form is over a year, but once mixed, the solution should be used within 48 hours, and usually within 24 hours.[79] Check with the manufacturer for recommended maximum storage times.

Mixing equipment must be designed and operated carefully to obtain the appropriate concentration and to feed the solution efficiently. The powder must be mixed thoroughly to avoid "fish eyes," or undissolved polymer particles. Thirty to 60 minutes is usually long enough to dissolve dry powders, but they should be mixed at a low speed (400 rpm) for 15 minutes to 3 hours to ensure complete dissolution.[80] The water should not be too warm (<120°F) or it may degrade the polymer.[81] Also, if the mixing water is chlorinated, make sure the residual is below 1 to 2 ppm because chlorine may degrade the product.[82] It may not be wise to use finished water for mixing.

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[79]Amirtharajah, p 51.
[80]Amirtharajah, p 54.
[81]Amirtharajah, p 51.
[82]Amirtharajah, p 52.

Polymers have long been recognized as helping improve coagulation. This is particularly true of natural polymers or biocolloids such as starch and starch derivatives, cellulose compounds, polysaccharide gums, and proteinaceous materials. These materials are polyelectrolytes which dissolve into charged particles that enhance coagulation of colloidal particles. The dose of natural polyelectrolytes is typically 1 to 10 mg/L.[71]

Use of synthetic polymers in water treatment is relatively recent. A 1979 AWWA survey of 336 water utilities[72] revealed that 50 percent of the utilities use or plan to use polyelectrolytes in water treatment. Most utilities use the polyelectrolytes with alum. The AWWA survey showed the following breakdown:

Types Used	Percent
cationic	55
cationic with anionic, nonionic, or both	18
anionic	12
nonionic	15

Anionic polymers are not as dependent on pH, alkalinity, hardness, or turbidity of the water, but their effectiveness is best within a narrow dosage range.[73] If too much anionic polyelectrolyte is added, the particles could be resuspended, so jar tests are important to determine the correct dose.

Synthetic polyelectrolytes are usually used at a dose of 0.1 to 1.0 mg/L[74] or at one-tenth the dose of the primary coagulant.[75] The AWWA survey found the average dose to be 0.4 mg/L when fed at the plant intake or rapid mix stage.

Coagulant aids are usually added at the end of the rapid mix or during slow mix, such as in the second floc compartment (Figure 7). Researchers say to add them from 2 to 6 minutes after the primary coagulant and to allow 7 to 10 minutes after addition for floc growth.[76] Tests were done on 18 polymers at a conventional treatment plant in Colorado treating low alkalinity river water.[77] Polymer coagulant aids enabled alum dosage to be reduced by almost 60 percent, and 30 to 40 percent less sludge was produced. Alum dose without coagulant aids was 28 mg/L. With 0.3 mg/L of cationic polyelectrolyte, only 12 mg/L of alum was needed.

Studies have examined the possible harmful effects of residual monomers in the potable water after use of the synthetic polyelectrolytes. Less than 0.05 percent of the remaining molecules are considered as an impurity.[78] Only those products approved by the Public Health Service should be purchased.

Storing and Feeding Coagulant Aids. Cationic polymers are usually in liquid form. Their handling and feeding requirements were discussed under Coagulants on p 36.

[71]"Water Quality and Treatment," p 99.
[72]"Survey of Polyelectrolyte Coagulant Use in the United States," p 601.
[73]"Water Quality and Treatment," p 98.
[74]"Water Quality and Treatment," p 98.
[75]Amirtharajah, p 61.
[76]Amirtharajah, p 62.
[77]Kasper, p 79.
[78]"Water Quality and Treatment," p 102.

Table 14

Typical Dosages and pH Range of Coagulants

Coagulant	Dose Range	Optimal pH Range
Alum	10 mg/L or less	6.8 - 7.5
Sodium Aluminate	5 mg/L or less	6.8 - 7.5
Iron salts	10 mg/L or less	5.5 - 8.8
Cationic polymer	0.5 to 10 mg/L	Variable

filter backwash has been done at municipal plants and at an Army water treatment plant. Unsettled filter backwash water could be blended with raw water at a ratio of 30 percent or less with the added benefit of a lower alum dose.[66] Recycling filter backwash also solves the problem where regulations prohibit discharging it back to the raw water source.

Recycling settled floc has also been known to improve flocculation when continuously recycled at a sludge to raw water ratio of 0.2 to 1 percent.[67] Recycled sludge should not be more than 2 or 3 days old to avoid taste and odor problems. Another drawback to recycling sludge is that constant chlorination is required to control bacteria growth.

Types of Coagulant Aids

Materials used as coagulant aids are bentonite clay, activated silica, and polymers.

Bentonite clay acts as a weighting agent to help stabilize and settle colloidal suspended matter. It is especially good for low mineral content, low turbidity, highly colored waters. It may also adsorb unwanted organic material (which could be contributing to THM problems). It should be added before the primary coagulant at a dose in the range of 10 to 50 mg/L[68] as determined by jar testing.

Activated silica helps improve coagulation, flocculation, and filtration. It produces a tougher floc, improves coagulation at low temperature and helps remove color. Activated silica is usually used with alum, at a rate of 7 to 11 percent of the alum dose.[69] If too much is used, the colloidal particles can be restabilized in suspension. Equipment can be purchased for producing activated silica on site. It has a limited storage period and must be prepared carefully to avoid gelling the feed solution.[70]

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[66]Kawamura, p 330.

[67]Kawamura, p 330.

[68]"Water Quality and Treatment," New York, *AWWA* (1971), p 95.

[69]"Water Quality and Treatment," p 96.

[70]"Water Quality and Treatment," p 94.
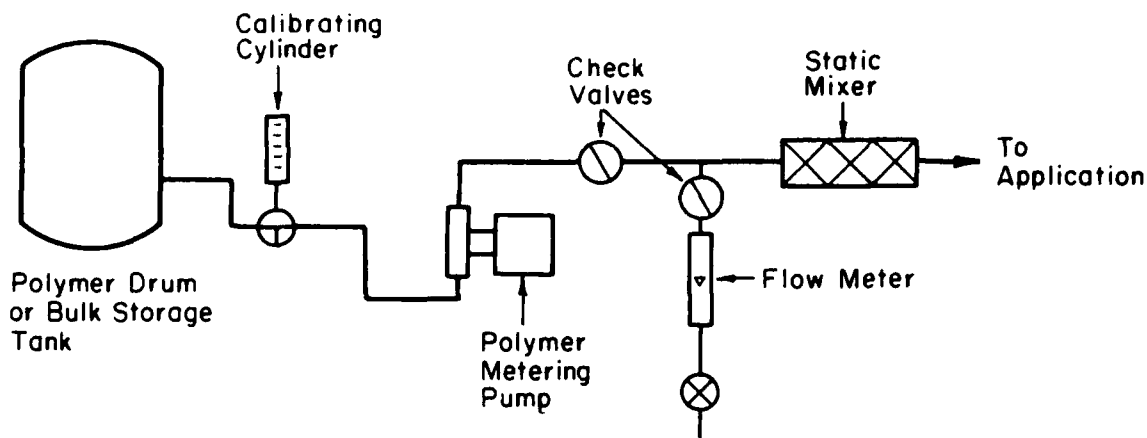
Figure 6. Liquid polymer feed system. (Reprinted from *AWWA Seminar Proceedings, Use of Organic Polyelectrolytes in Water Treatment,* A. Amirtharajah, "System Design for Polymer Use," by permission. Copyright © 1983, The American Water Works Assocation.)

● Settled water turbidity

● Length of time to reach a desired turbidity

● Volume of sludge created

● How easily sludge is dewatered

● Optimal pH and acid or base needed to achieve it

● Ease of storing and handling coagulant

Use of Coagulant Aids. Chemical or other coagulant aids may be employed along with the primary coagulant to improve clarification in several ways. They may act as a "seed" to help clarify low turbidity water, or can widen the optimal pH range for a given dose of coagulant. They help produce a larger, stronger, more settleable floc so the overflow rate on the clarifier can be increased. Better removal by settling and the creation of stronger floc improves filtration, leading to a higher filtration rate or longer filter runs. These advantages have significantly increased the capacity of existing plants without capital expenditure for new equipment.

Other advantages to using coagulant aids are that alum (or other primary coagulant) dose may be decreased, and less caustic is needed for pH adjustment after clarification. Because less alum is added, less sludge is produced and it can be handled and dewatered more easily, also contributing to cost savings. Synthetic coagulant aids (polyelectrolytes mentioned earlier) can be tailored using certain molecules to handle specific water quality problems such as color or bacteria and virus removal.

In addition to chemical coagulant aids, discussed in detail in the next section, other aids are available. Filter backwash water may be used as a seed to improve coagulation and flocculation, especially for raw water with low turbidity. Continuous recycling of

Table 13 (Cont'd)

Manufacturer	Produce Name	Typical Dose, ppm**	Maximum Allowable Dose, ppm	Molecular Weight (Lo-Mid-Hi)	Chlorine Resistant	Other
Purpose:	**Primary Coagulant or Coagulant Aid (cont'd)**					
Type:	**Granular Powder**					
Allied Colloids	Percol LT 20		1	Very Hi		All in 50-lb bags or bulk.
	Percol LT 22		1	Mid		
	Percol LT 22S		1	Very Hi		
	Percol LT 24		5	Lo		
	Percol LT 25		5	Hi		
	Percol LT 26		1	Hi		
	Percol LT 27		1	Very Hi		
Purpose:	**Coagulant Aid**					
Type:	**Dry Powders - Anionic**					
Betz	1100P	0.1-3				
Calgon	Coagulant Aid 243		25	Hi		50-lb. bags (Both in 25-lb bags)
	Coagulant Aid 253		1	Hi		
			1	Hi		
Type:	**Dry Powders - Nonionic**					
Calgon	Coagulant Aid 244		1			25-lb. bag
Type:	**Emulsion - Anionic**					
Calgon	L675 Emulsion Polymer		4	Hi		
Type:	**Natural Materials (Pulverized Clay)**					
Calgon	Coagulant Aid 25	3-20				All in 50-lb. bags.
	Coagulant Aid 35	3-20				
	Coagulant Aid 36	3-20				

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Table 13 (Cont'd)

Manufacturer	Produce Name	Typical Dose, ppm**	Maximum Allowable Dose, ppm	Molecular Weight (Lo-Mid-Hi)	Chlorine Resistant	Other
Purpose: Primary Coagulant or Coagulant Aid						
Type: Liquid Cationic						
Calgon	Catfloc C		25		Yes	
	Catfloc R		100		Yes	
	Catfloc B				Yes	Also in 40-lb pails
Allied Chemical	Clarifloc Polymer C-305P	5-100	50			
American Cyanamid	Magnifloc 572C	1-20 as primary coagulant,	20	Lo	Yes	
	Magnifloc 573C		20	Lo	Yes	
	Magnifloc 575C		20		Yes	
	Magnifloc 577C	0.5-5.0 as coagulant aid.	20	Mid	Yes	
	Magnifloc 579C		20		Yes	
	Magnifloc 581C		20	Hi	Yes	
Calgon (amine-type)	CA 250		20	Lo		
	CA 289		50	Lo		
	CA 260		20	Hi		Bulk Only
Allied Colloids (organic)	Percol LT 35			Lo		
	Percol LT 31			Lo		

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Table 13

Typical Coagulants Approved for Potable Water Treatment*

Manufacturer	Produce Name	Typical Dose, ppm**	Maximum Allowable Dose, ppm	Molecular Weight (Lo–Mid–Hi)	Chlorine Resistant	Other
Purpose: Primary Coagulants **Type: Liquid Cationic**						
Calgon	Catfloc K-5	5–40	150		Yes	
	Catfloc K-10	5–40	275		Yes	
	Catfloc A		80			
	Catfloc T		50			
Betz	Polymer 1190	2–10	25	Lo	Yes	
	Polymer 1192	2–10	25	Mid	Yes	
	Polymer 1195	2–10	25	Mid	Yes	
Nalco			150	Lo	Yes	
Allied Chemical	Clarifloc Polymer C-308P	0.5–5	50	Lo	Yes	Organic
Western Chemical	WestoFloc 13					

*This is a sample of the products available from a few manufacturers and is not all-inclusive, nor does it constitute, endorsement of these products. All products are available in 55-gallon drums or in bulk, unless otherwise noted. Corrosion resistant materials should be used for all mixing and feeding facilities.

**The dosages shown (based on manufacturer's literature) are typical ranges. To compare two products, jar tests should be conducted on raw water to determine the required dosage for each. Then costs may be estimated and two or more products compared.

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Cationic	Anionic	Nonionic
⊕ ⊕ ⊕ ⊕ ⊕	⊖ ⊖ ⊖ ⊖	○ ○ ○ ○
Break Up Into Positively Charged Molecules When Dissolved.	Break Into Negatively Charged Molecules When Dissolved.	Break Into Molecules With No Charge.
Use As Primary Coagulant Or As Coagulant Aid.	Use As Coagulant Aid.	Use As Coagulant Aid.
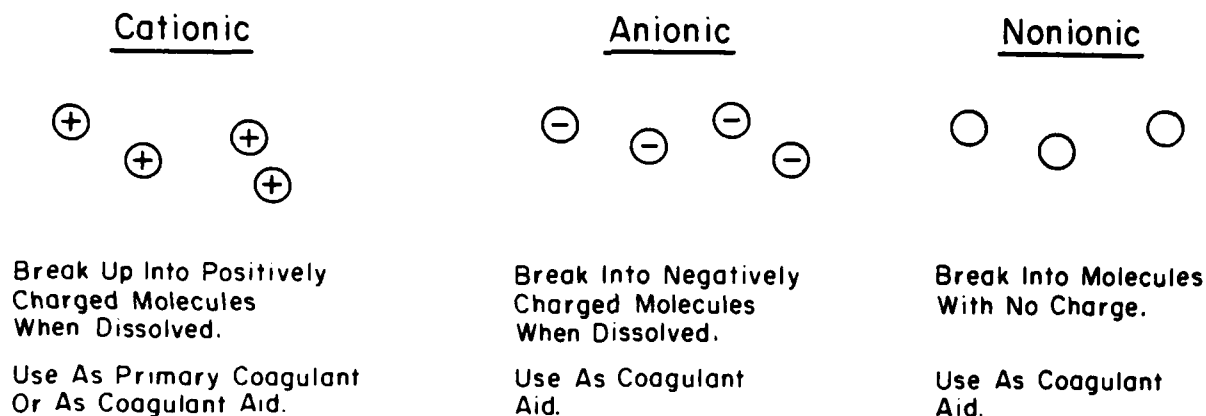
Figure 5. Types of polyelectrolytes.

Other considerations are freeze protection of the cationic polymer during shipment and storage, and a limited shelf life of from 3 to 12 months.[62] Exposure to air will also decrease its effectiveness. Storage and feed tanks should be thoroughly cleaned with salt solution or by steaming before switching to a new product. Another precaution is that some cationic polyelectrolytes may lose effectiveness when exposed to residual chlorine[63] so sensitivity to chlorine should be checked with the manufacturer.

Coagulant Dosage. Typical dosages and optimal pH range for the coagulants are shown in Table 14.

Raw Water Characteristics (pH, Turbidity, Chemical Composition). The nature of the colloidal matter suspended in the raw water will determine the optimum pH and co-agulant dose range and whether it is worthwhile to use a coagulant aid. If a surface water has a lot of bentonite clay particles, the optimum pH range for good coagulation will be wider than if the water has a lot of kaolinite clay suspended matter.[64] Also, bentonite is more capable of being destabilized by the coagulant than koalinite or silica particles.[65] Adding bentonite as a coagulant aid may allow suspended colloidal material to be destabilized more easily, especially if the surface water has a lot of kaolinite sus-pended particles.

The proper type of coagulant and optimum dose, pH, and mixing time should be de-termined in the lab using jar tests. The tests should be carried out at the same tempera-ture as the water in the plant. The following criteria should be evaluated:

● Chemical dose and cost

● Mixing time

● Settleability of floc (floc size and density)

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[62] Amirtharajah, p 53.
[63] Kawamura, p 329.
[64] Kawamura, p 331.
[65] Kawamura, p 329.

Certain types of polyelectrolytes can be used as coagulants. Polyelectrolytes are natural or synthetic polymers (long chains of molecules) which break up when dissolved in water. Figure 5 shows three types of polyelectrolytes: anionic, nonionic, and cationic. There are 600 USEPA-approved polyelectrolyte formulas that may be used in water treatment.[55] Cationic polyelectrolytes are used as primary coagulants or coagulant aids. Anionic and nonionic polyelectrolytes are used as coagulant aids and are discussed later in this chapter. Table 13 shows manufacturers and properties of synthetic coagulants.

Cationic polyelectrolytes are composed of molecular chains with positive ions. They break up into positively charged cations when dissolved in water. Since cations can neutralize the negative charge on the surfaces of clay colloidal particles and overcome the repulsive forces, they can be used in place of alum as the sole coagulant. A 1979 American Water Works Association (AWWA) survey showed that 17 out of 129 water utilities use cationic polyelectrolytes as the sole coagulant.[56]

The main advantage of cationic polyelectrolytes over alum or iron salts is that they do not lower the pH as much; thus less time or caustic is needed later for pH adjustment. Also, the floc produced settles more easily so the overflow rate of the settling basin can be increased. Another advantage is that less sludge is produced.[57] Since the sludge does not contain as much aluminum or iron, it may more easily meet regulatory discharge limits if it is to be treated and discharged back to the surface water source.

Cationic polyelectrolytes are often available in liquid form: 5 gal pails, 55 gal drums, or 5000 gal tankers. The product could be diluted 10:1 with water, mixed for 10 minutes to thoroughly dissolve it, and then pumped to a feed tank before adding to the rapid mixer. (An existing feed tank could be used.) Alternatively, the liquid could be metered directly from the drum into a static mixer, where it would be diluted to 1 percent or less (preferably 0.1 percent) before injection to raw water.[58] Figure 6 shows how this system would be set up.

The viscosity of the liquid may be as low as 50 to 100 centipoise or as high as 5000 to 10,000 centipoise; the more viscous types may need pumps with larger suctions and discharge lines. Most metering pumps will not have trouble if viscosity is less than 2000 centipoise.[59] A hydraulic diaphragm pump is recommended because it is less susceptible to clogging.[60] A pulsation dampener on the metering pump from the feed tank may be needed to avoid the on-off effect and ensure uniform feed of the coagulant.

Since the pH of the cationic polymer solution could be anywhere from 2 to 11,[61] all tanks, pumps, lines and fittings should be made of resistant materials such as plastic, fiberglass, or 18-8 stainless steel.

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[55] M. C. Kavanaugh, "Introduction," *AWWA Seminar Proceedings, Use of Organic Polyelectrolytes in Water Treatment*, Las Vegas, NV (June 5, 1983), p vii.

[56] "Survey of Polyelectrolyte Coagulant Use in the United States," Committee Report, *JAWWA*, Vol. 74 (1982), p 602.

[57] Kasper, p 74.

[58] A. Amirtharajah, "System Design for Polymer Use," *AWWA Seminar Proceedings, Use of Organic Polyelectrolytes in Water Treatment*, Las Vegas, NV (June 5, 1983), p 55.

[59] Amirtharajah, p 55.

[60] Amirtharajah, p 56.

[61] Amirtharajah, p 55.

Checklist for Improving Coagulation/Flocculation

Table 17 is a summary checklist of operational changes and minor design changes which should be considered for improving coagulation/flocculation at existing water treatment plants. It should be reviewed as a starting point for identifying potential areas of improvement. The feasibility and effectiveness of each suggestion will depend on the conditions at each installation.

Improving Clarification

After coagulation and flocculation, the floc particles are allowed to settle out (clarified), producing a clear effluent with most turbidity removed.

Settling basin capacity can be doubled by adding tube or plate settlers, also known as lamella separators. These have been used widely in Europe and are gaining popularity in the United States. They increase the surface settling area, so detention time can be decreased to as little as 10 minutes.[93]

Plate settlers are plastic plates inclined at an angle up to 60 degrees from horizontal. The water flows across the plates and suspended particles settle and slide down the sides, aided by the steep angle (Figure 10).

Tube settlers are also inclined up to 60 degrees from the horizontal, but water flows upward through the tubes while particles settle and slide downward. Figure 11 shows the configuration for shallow and steep tube settlers. Either type may be installed in an existing circular or rectangular basin. Tube settlers are made of high-strength, lightweight plastic, simply supported by lightweight structural members. (One utility commented that the flammable plastic was a fire hazard and recommended polyvinyl chloride material.[94]) Usually they are available in modules 2.5 to 3 ft wide and 10 ft long, with overflow rates of 2 gpm/sq ft over the entire basin.[95] A USEPA estimate for adding a tube settler (including tubes, supports, anchor brackets, transition and effluent baffles, plus installation costs) for a 1 mgd plant is $10,000.[96]

Tube settlers were installed in an existing settling basin at the municipal plant in Willimantic, Connecticut. Alonr vith other modifications such as adding a polymer coagulant aid and improving coagulation and flocculation, this enabled the plant to double its capacity from 3 to 6 mgd.[97]

Plant tests were conducted on tube settlers installed in existing basins at a Potomac River filtration plant. Results showed a 34 percent reduction in solids leaving the settling basin,[98] meaning a significant decrease in filter loading. Plate settlers had

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[93] Weber, p 130.

[94] W. Fallin, Washington Suburban Sanitation Commission, Personal Communicacation, April 27, 1984.

[95] *Estimating Water Treatment Costs*, Vol. 2, EPA 600/2-79 (USEPA, 1979), p 142.

[96] *Estimating Water Treatment Costs*, pp 146-147.

[97] Roy, Superintendent, Water Treatment Plant, Willimantic, CT, Personal Communication, May 1984.

[98] *Upgrading Study—Potomac Water Filtration Plant* (Washington Suburban Sanitary Commission, September 1978), p D-1.

Table 17

Items to Consider for Improving Coagulation/Flocculation

- Mix the coagulant as rapidly and uniformly as possible to achieve the most effective coagulation (mixing time less than 1 minute).

- The coagulant solution should be a low concentration (less than 0.5 percent) to achieve more uniform mixing.

- Avoid delay between mixing the coagulant and feeding the coagulant solution to the water. Otherwise the coagulant products will be formed without having contacted the raw water.

- Take advantage of hydraulic energy in the system for mixing coagulant. If there is enough turbulence it may be worthwhile to move the coagulant injection to this point.

- Feed the coagulant continuously to achieve more uniform mixing, rather than with a pulsed effect created by on/off control systems.

- Consider a hydraulic eductor or pump injection for flash mixing.

- Consider an in-line blender with variable speeds to handle different flow rates through the plant.

- A coagulant feed system using orifices (facing upstream) may help achieve more uniform mixing, especially if there is turbulence, but this type may get clogged more easily.

- If flow measurements are used for determining coagulant dosage, make sure they are accurate so proper dose is applied.

- If raw water flow is split and each stream receives coagulant, make sure coagulant dose to each stream is correct based on proportion of flow.

- Use turbidimeters located after the filters to adjust coagulant dosage periodically, avoiding waste.

- Conduct jar tests to make sure coagulant dosage is optimal for the pH and alkalinity of the water.

- Make sure mixing is continuous and avoid delays between mixing and floc stages.

- The detention time in the floc basin should be at least 20 minutes.

- Compartmentalize the floc basin into three or more compartments and have lower mixing intensity in each successive compartment (tapered mixing).

- Make sure flocculation is continuous.

- Consider using axial flow impellers instead of paddles to improve floc formation.

- Add baffles or weirs in the floc basin to lengthen detention time and avoid carryover of too-small particles.

- Submerged exit ports from the floc basin may need to be enlarged to avoid excessive turbulence and shear which would break up the particles.

- A coagulant/flocculant aid may be desirable to produce a tougher, more settleable floc, with less sludge formed and better finished water quality.

- Consider filter backwash as a coagulant/flocculant aid.
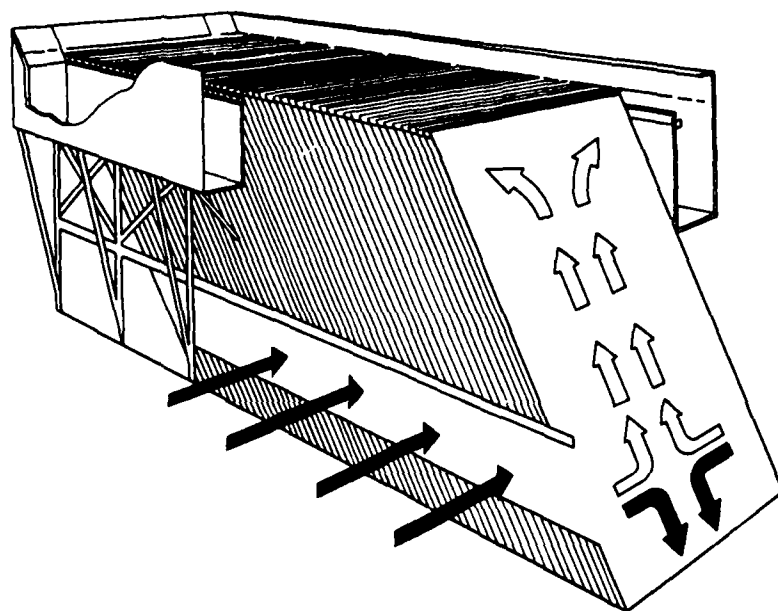
Figure 10. Plate settler. (Reprinted from *Journal AWWA*, Vol. 72, No. 5 (May 1980), R. E. Forbes, et al., "Upgrading Water Treatment Plants: An Alternative to New Construction," by permission. Copyright © 1980, The American Water Works Association.
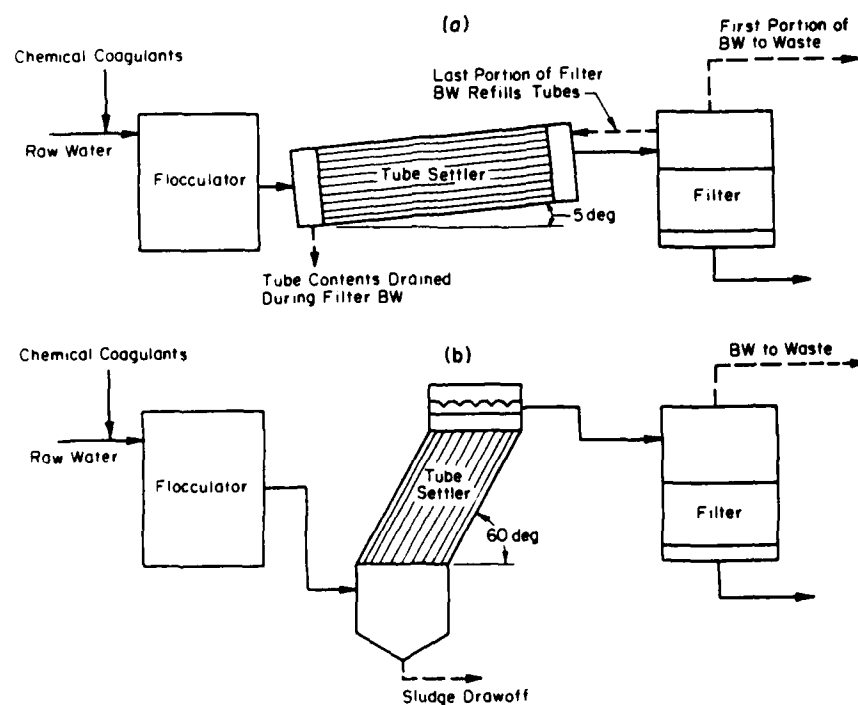
Figure 11. Tube settlers. (Reprinted from W. J. Weber, *Physiochemical Processes for Water Quality Control*, 1972, with permission from John Wiley & Sons, Inc.)

also been tested at the plant but there was no noticeable improvement in effluent suspended solids concentration.[99]

Plants installing tube or plate settlers also made other modifications to improve plant performance;[100] e.g., switching to a more effective coagulant and optimizing the dosage for pH and alkalinity, using a coagulant aid, altering the rapid mix basin to distribute the coagulant more effectively, compartmentalizing the flocculators, and having sequentially decreasing mixing speeds in the flocculator compartments. The cost of these modifications should be evaluated before deciding to install tube or plate settlers. Their major advantage appears to be increased plant capacity, but this may not be a high priority at Army plants. If increasing treatment plant capacity is an objective, then tube or plate settlers should be considered along with the above improvements.

Other ways to improve clarification would be to install baffles and weirs to improve flow distribution and lengthen detention time, and to install screens onto the sides to protect from wind. Wind-induced currents may cause short circuiting and possible carryover of solids.

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[99]Fallin, Personal Communication, April 27, 1984.
[100]*Upgrading Study-Potomac Water Filtration Plant*; Forbes, p 257; Prendiville, p 67.

6 CORROSION

Impact on Army Installations

Corrosion is a large problem on Army installations, particularly because many are 40 or more years old.[101] The problems of pipe leakage or rupture and loss of carrying capacity are quite evident. Pump replacements and pipe repairs and replacements increase labor and materials costs. Clogging and deposits of corrosion products increase pumping costs, cause reduced water pressure, and retard heat transfer.

In addition to the high cost, health effects are of concern because of the presence in drinking water of metals released from corroding pipes. Agency surveys have found iron, lead, zinc, cadmium, copper and several other metals in tap water.[102] In Boston, where lead pipes have been used since the late 19th century, excessive levels of lead have been found in drinking water due to the corrosive waters with low alkalinity and low hardness.[103] Corrosion of the matrix of asbestos cement pipe can release asbestos fibers, which are suspected by some to be a health hazard.[104]

Because so many different compounds have been used to manufacture asbestos cement pipe, the exact composition and the solubility of any given pipe is unknown. This makes it hard to predict the susceptibility of the pipe matrix to corrosion or to prescribe protective water treatment. Because of these concerns, the USEPA set limits on concentrations of inorganic chemicals in drinking water in the National Interim Primary Drinking Water Regulations[105] and the National Secondary Drinking Water Regulations.[106] Regulations proposed in October 1983 would require water suppliers to monitor water for characteristics of corrosivity as well as to report on the materials of construction of the distribution system.[107]

Factors Affecting Corrosion

Corrosion originates from "rodere," the Latin word meaning "to gnaw." When pipes corrode, iron returns to its natural oxidized state and releases electrons. The electrons

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[101]C. Hahin, *Effects of Corrosion on Military Facilities of the Presidio of San Francisco,* Interim Report M-254/ADA058727 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], August 1978), pp 5 and 8; C. Hahin, *Corrosion Cost of Air Force and Army Facilities and Construction of a Cost Prediction Model,* Technical Report M-224/ADA042628 (USA-CERL, July 1977), pp 2 and 14.

[102]G. J. Kirmeyer, "Principles of Internal Corrosion and Corrosion Monitoring," *JAWWA,* Vol. 75 (1983), p 81.

[103]P. C. Karalekas, "Control of Lead, Copper and Iron Pipe Corrosion in Boston," *JAWWA,* Vol. 75 (1983), p 94.

[104]M. R. Schock and R. W. Buelow, "The Behavior of Asbestos Cement Pipe Under Various Water Quality Conditions: Part 2, Theoretical Considerations," *JAWWA,* Vol. 73 (1981), p 638.

[105]National Interim Primary Drinking Water Standards, 40 FR 59570, December 24, 1975.

[106]National Secondary Drinking Water Regulations, 44 FR 42198, July 19, 1979.

[107]National Revised Primary Drinking Water Regulations, Federal Register 48:194:45502, October 5, 1983.

react with water and oxygen to form hydroxide ions or, under acidic or anaerobic conditions, with hydrogen ions to liberate hydrogen gas.

$$Fe \rightarrow Fe^{+2} + 2e^- \quad \text{(anode)}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad \text{(cathode)}$$

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{(cathode)}$$
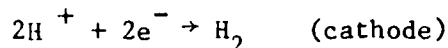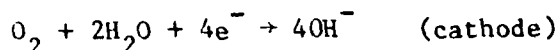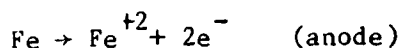
The metal goes into solution at the anode and the hydroxide ions or hydrogen gas are formed at the cathode. Figure 12 illustrates these reactions. Corrosion can dissolve the pipe walls uniformly (usually in copper pipes) or in localized pits which develop into leaks and eventually cause the pipe to rupture.

Tubercules are formed on pipe surfaces when iron ions are oxidized and ferric hydroxide precipitates:

$$2Fe^{+2} + 5H_2O + 1/2O_2 \rightarrow 2Fe\,(OH)_3 + 4H^+$$
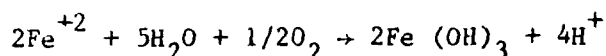
The tubercules interfere with flow and reduce the carrying capacity of the pipe.

Several factors affect the rate of corrosion: pH, alkalinity, temperature, and dissolved oxygen content of the water; velocity in the lines; and the presence of minerals, CO_2, bacteria, or debris.

The pH and alkalinity determine the ability to precipitate from the water a protective calcium carbonate film on the interior pipe surfaces.

At higher temperature, some corrosion prevention chemicals such as polyphosphates become ineffective. Also, in hot water some minerals may precipitate on pipe surfaces (scaling), causing loss of carrying capacity and inhibiting heat transfer.

Dissolved oxygen participates in the chemical reaction at the cathode and serves as a driving force for corrosion. If the velocity in the pipes is higher, there is more turbulence, bringing more oxygen to the pipe walls, and corrosion progresses.

The presence of ions (especially chloride, sulfate, ammonium, and sulfide) increases the current-carrying capacity of the water, so electrons released at the anode can migrate more easily to the cathode. Water low in alkalinity, calcium, and hardness, and/or high in chloride or sulfate ions is more likely to be corrosive. Experiments have shown that corrosion increased when free chlorine residual was above 0.4 ppm.[106]

Dissolved CO_2 in the water forms carbonic acid, which may react with iron to promote corrosion. The increased acidity due to the CO_2 also can inhibit the formation of a protective film on pipe surfaces.

Bacteria (iron bacteria) or debris on the pipes provide shelter for sulfate-reducing bacteria, which under anaerobic conditions create an acidic environment that promotes corrosion. If iron bacteria are present, they consume hydroxide at the cathode, also providing a driving force for corrosion.

*D. T. Merrill, *Corrosion Control by Deposition of CaCO₃ Films: A Handbook of Practical Application and Instruction*, AWWA, Denver, CO (1978), p 36.

Reactions:

1. Hydrogen Evolution (Acids):

$$2H^+ + 2e^- \rightarrow 2H \rightarrow H_2$$

2. Oxygen Reduction (Natural Waters):

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Cathode

Anode — Metal Dissolution $Fe \rightarrow Fe^{+2} + 2e^-$
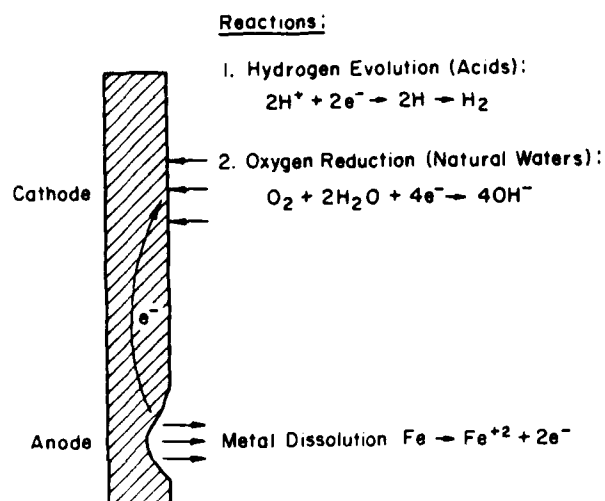
Figure 12. Corrosion reactions on metal pipe. (Adapted from: L. D. Benefield, J. F. Judkins, and B. L. Weand, *Process Chemistry for Water and Wastewater Treatment*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1982).

Corrosion Prevention

Corrosion prevention should encompass a number of interdependent activities (Table 18), including:

● Routinely analyzing raw water for corrosive tendencies and proper chemical treatment

● Monitoring for evidence of corrosion in the distribution system

● Flushing the lines as needed

● Carefully selecting materials in the distribution system

● Applying pipe linings

● Installing cathodic or other types of pipe protection.

This report focuses on treatment to stabilize the water so it does not corrode or cause scaling; pipe linings and external pipe protection such as cathodic protection are discussed in TM 5-811-4.[109]

The treatment processes affecting corrosion are listed in Table 19 along with the key O&M criteria for these processes.

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[109]*Electrical Design, Corrosion Control,* Technical Manual (TM) 5-811-4 (Department of the Army, August 1962).

Table 18

Elements of an Effective Corrosion Control Program

Water Treatment Plant	Monitoring in the Distribution System
Routine Water Sampling & Analysis	Coupon tests
Calculate Calcium Carbonate Precipitation Potential	Pipe inserts (ASTM)
Marble test to measure $CaCO_3$ Precipitation Potential	Water sampling & analysis
Determine correct chemical dosage	Staining tests
Record treatment practices	Records of customer complaints

Other Activities	Records of pipe hydraulic characteristics, test, etc.
Pipe cleaning/scraping/relining	
Pipe coatings (external)	Observations of pipe condition when excavations made
External protection (galvanic, induced current, etc.)	Pipe rupture/repair records
Pipe flushing	

Table 19

Processes Related to Corrosion and Key O&M Criteria

	Treatment Understanding	Process Monitoring and Control	Preventive Maintenance	Analytical Capabilities
Chemical Dosage	x	x		x
Coagulation/ Flocculation	x			
Softening	x	x	x	x
Stabilization	x	x		x

Calcium Carbonate Protection

Ideally, the water should not dissolve or deposit calcium carbonate, but a thin protective film of calcium carbonate should be maintained on interior pipe surfaces. Desirable water characteristics to accomplish this have been identified as follows:[110]

● The water should be oversaturated with $CaCO_3$ in the range of 4 to 10 mg/L as $CaCO_3$ (meaning that $CaCO_3$ has precipitated).

● Calcium and alkalinity should each be at least 40 mg/L (expressed as $CaCO_3$).

● The ratio of alkalinity to the sum of the chloride and sulfate ions (all expressed as $CaCO_3$) should be at least 5:1.

● The pH should be in the range of 6.8 to 7.3.

Determining the corrosivity of the water and the treatment needed requires laboratory tests or use of corrosion indices and/or diagrams as described below. Routine sampling and analysis of raw water for corrosive tendencies should include measurement of temperature, pH, hardness, alkalinity, calcium, and total dissolved solids.

The Caldwell-Lawrence (C-L) diagrams can be used to determine if raw water is saturated with calcium carbonate, and if not, what doses of chemicals would achieve saturation. There are separate diagrams for various levels of water temperature and total dissolved solids. Merrill gives clear guidelines for using the Caldwell-Lawrence diagrams.[111]

Lime, soda ash, caustic soda, bicarbonate of soda, or CO_2 may be added to achieve the desired water characteristics. Alum coagulation can remove some of the calcium and alkalinity needed to maintain a protective calcium carbonate film. In European water treatment plants, where alum coagulation can reduce raw water alkalinity to below 25 ppm, lime or calcium chloride plus carbonate alkalinity are added after coagulation. This brings finished water alkalinity to 100 to 150 ppm as $CaCO_3$ at pH 8 to 8.5, providing enough alkalinity to form a protective coating.[112]

The Marble Test can be conducted on the finished water to check for calcium carbonate saturation, and to measure the calcium carbonate precipitation potential. This test is conducted as follows.[113]

1. Split a sample of finished water into two parts.

2. Measure the calcium concentration of the first part.

3. Place the second part in a stoppered bottle. Add 0.1 to 0.2 grams of finely divided $CaCO_3$ before sealing the bottle. (The sample should fill the bottle completely; a biochemical oxygen demand bottle is ideal.) Mix by rapidly inverting the bottle as often

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[110] Merrill, p 37.

[111] Merrill, p 36.

[112] J. W. Patterson, "Corrosion Inhibitors and Coatings," *AWWA Seminar Proceedings, Controlling Corrosion Within Water Systems*, Atlantic City, NJ (June 25, 1978), p 3.

[113] Merrill, p 36.

as possible over the next few hours. Allow the samples to stand overnight--if possible, at the temperature of the process stream.

4. The next day, filter the supernatant from the second part and measure the calcium concentration of the filtrate.

5. If the calcium concentration of the filtrate from the second part is less than the calcium concentration of the first portion, $CaCO_3$ has precipitated and the $CaCO_3$ precipitation potential of the water tested is equal to the difference in the two calcium values. If the calcium concentration of the second portion exceeds that of the first, the water tested is undersaturated. If there is no difference, the water is saturated.

If the calcium carbonate precipitation potential differs much from the potential calculated based on the C-L diagrams, the calculations and chemical analysis of the finished water should be checked for errors. Note that the temperature and total dissolved solids of the C-L diagram may not have been identical to that of the water, which would introduce some error. Another reason for discrepancy between measured and calculated precipitation potentials may be the presence of chemical species not considered in the construction of the C-L diagram.[114] If the reason for the discrepancy cannot be found, the chemical dosages should be adjusted so the measured precipitation potential via the Marble Test matches the desired (calculated) value. Use of other chemicals to create a protective film may also be desirable.

Other Protective Films

Chemicals such as silicates or complex phosphates can be added to produce a protective film other than calcium carbonate. This treatment is particularly attractive where raw water characteristics do not allow use of the C-L diagrams or where adding chemicals to create an adequate calcium carbonate precipitation potential would be uneconomical; i.e., in water with very low alkalinity or calcium content.

Chemical selection is based on materials in the distribution system and water characteristics. There are a number of products on the market composed of silicates, phosphates, or a combination thereof, with different protective mechanisms. Laboratory tests, if possible, and cost analysis should be conducted in making a selection and determining proper dosage.

Table 20 summarizes results of 120-day field testing done by the Illinois State Water Survey on use of various corrosion-inhibiting chemicals at several State facilities and Air Force installations.[115]

Liquid sodium silicate was used in doses of 8 to 10 ppm. Zinc silicate with sulfamic acid (formulation: 8 ppm SiO_2 as liquid silicate + 3 ppm Zn^{++} as $ZnSO_4 \cdot H_2O$ + 1 ppm sulfamic acid as HNH_2SO_3) was used at 8 ppm.

[114] Merrill, p 37.
[115] T. E. Larson, *Corrosion by Domestic Waters*, Illinois State Water Survey, Urbana, IL (1975), p 31.

Table 20

Chemical Treatment for Inhibiting Corrosion in Hot Water Systems[a]

Approximate Water Characteristics	Pipe Composition	
	Copper, 90:10 Copper:Nickel	Galvanized Steel
Low hardness (20 ppm) Low alkalinity (20 ppm) Total dissolved minerals 75 ppm	Liquid sodium silicate (8 ppm SiO_2) Zinc polyphosphate[b] (5 ppm) Zinc monobasic phosphate[c] (6 ppm) (pH 7.0)	Liquid sodium silicate (pH 8.4, temp. 140-180°F)
Low hardness (6 ppm) High alkalinity (340 ppm) Chloride plus sulfates = 200 ppm	Zinc polyphosphate (5 ppm) (pH 7, temp. 140-180°F)	Liquid sodium silicate (10-20 ppm as SiO_2) (pH 8-8.3)
Medium hardness (65-90 ppm) High alkalinity (350 ppm) Chloride plus sulfates = 180 ppm, pH 7.8-8.1	Zinc monobasic phosphate (6 ppm) Zinc silicate[d] (8 ppm) (temp. 140°F) Zinc monobasic phosphate (6 ppm) (temp. 180°F)	Liquid sodium silicate (11-22 ppm SiO_2) (pH 8.1) Zinc silicate (8 ppm SiO_2) (pH 7.8)
Higher hardness (150 ppm) Alkalinity (120 ppm) Chloride plus sulfate = 300 ppm, pH 6.8	Liquid sodium silicate (8 ppm SiO_2) (temp. 140°F) Zinc silicate (8 ppm SiO_2) (temp. 180°F) (pH adjusted to 8.3)	Liquid sodium silicate (10 ppm SiO_2) (pH adjusted to 7.8, temp. 140°F)
Hardness 70-80 ppm Alkalinity 260 ppm Chloride plus sulfate = 600 ppm	Copper-liquid silicate (11-22 ppm SiO_2) Copper, copper:nickel – zinc silicate (8 ppm SiO_2) (pH 8.2, temp. 140-180°F)	Liquid sodium silicate (11-2 ppm SiO_2) (pH 8.1, temp. 140-180°) Zinc monobasic phosphate (6 ppm) (pH 7.7, temp 180°F)

[a]Reprinted by permission from T. E. Larson, *Corrosion by Domestic Waters* (Illinois State Water Survey, Urbana, IL, 1975).

[b]inc polyphosphate formulation – U.S. Patented formula by Calgon, Inc. Zinc polyphosphate, composed of: phosphorus pentoxide (P_2O_5) – 56.5%; zinc oxide (ZnO) – 11.0%; and sodium oxide (Na_2O) – 32.5%.

[c]Zinc monobasic phosphate formulation – U.S. Patent 3669616 formula by Virginia Chemicals, Inc.: zinc sulfate ($ZnSO_4$ H_2O) – 55.3%; sulfamic acid (HNH_2SO_3) – 20.0%; and sodium monobasic phosphate (NaH_2PO_4) – 24.7%.

[d]Zinc silicate formulation – 8 mg/L SiO_2 (as liquid silicate) + 3 mg/L Zn^{++} (as $ZnSO_4$ H_2O) + 1 mg/L sulfamic acid (as HNH_2SO_3).

Silicate treatment (as Na_2O and SiO_2) has also been found by others to be more effective in waters with low hardness and alkalinity and low pH (> 8.4) with high velocity.[116] Silica may be adsorbed in the hydroxide corrosion products of iron and copper,[117] or as studies of asbestos cement pipes have shown, silicates may act as a sequestering agent for ferric iron in solution, co-precipitate with metal complexes, or bind with metals to form a protective coating.[118]

Various forms of phosphate compounds such as polyphosphates, sodium hexametaphosphate, metallic orthophosphates, and bimetallic phosphates have been used for corrosion control at Army installations. The polyphosphates offer limited protection in hot water systems because they revert to the ineffective orthophosphate form above 150°F. Also, they perform best if velocity is between 2 and 5 ft/sec and offer little protection in stagnant areas. Studies have shown that a minimum dose of phosphate compound was needed--usually at least 15 to 25 ppm--to afford protection.[119],[120] Such high dosages would promote growth of microorganisms in the distribution system and would not be practical. The waste water would also have higher phosphate levels and could cause eventual eutrophication of the receiving water body and may necessitate phosphate removal by the sewage treatment plant. If total alkalinity, pH, and calcium concentrations were increased, this minimum dosage decreased.[121]

Bimetallic phosphates have become more popular in municipal and Army water treatment plants. These compounds are reputed to form a protective coating. The Philadelphia Suburban Water Company conducted studies over three decades while testing the effectiveness of corrosion control chemicals on the distribution system. They found bimetallic phosphate effective for cast iron over a wide velocity range (0.5 to 2.0 ft/sec), and for copper if pH was above 7.0.[122] Experience at Army installations has been that bimetallic phosphates protect a wider range of materials in the distribution system.

Zinc orthophosphate is being used at municipal water treatment plants and will soon be tested at Army plants. The Middlesex Water Company of Woodbridge, NJ, uses a dose of 1.5 to 2.5 mg/L of product (amounting to about 0.25 to 0.5 mg/L of zinc) in their distribution system that has pipes 80 years old, some of which are unlined.[123] Their surface water is very aggressive and this practice effectively controls corrosion. Earlier, they had conducted laboratory tests to compare pH adjustment alone with bimetallic phosphate and with zinc orthophosphate, both with pH adjustment. The pH was adjusted to 6.6 to 7.0 with 2 to 4 mg/L of caustic soda, and water was pumped through a metering pump and the chemical diffused into the contact chamber. The dose was changed slightly as water temperature varied with the season.[124] Bimetallic phosphate combined with pH

[116]"Water Quality and Treatment," p 308.
[117]"Water Quality and Treatment," p 308.
[118]Shock and Buelow, p 648.
[119]Larson, p 31.
[120]S. K. Banerji, "Polyphosphate Additions for Corrosion Control in Water Distribution Systems," *Proceedings of the American Society of Chemical Engineering (ASCE) 1983 National Conference on Environmental Engineering*, Boulder, CO (1983), p 105.
[121]Banerji, p 105.
[122]K. E. Shull, "An Experimental Approach to Corrosion Control", *JAWWA*, Vol. 72 (1980), p 284.
[123]J. A. Ritter, Personal Communication (21 May 1984).
[124]E. D. Mullen, "Monitoring and Controlling Corrosion by Potable Water," *JAWWA*, Vol. 72 (1980), p 290.

control reduced the corrosion rate by only 13 percent, whereas the zinc orthophosphate with pH adjustment reduced it by 79 percent.

The Hackensack Water Company at Weehauken, NJ, has also tested zinc ortho-phosphate.[125] Their raw water is aggressive and parts of the distribution system are un-lined pipe 100 years old. Coupons were installed upstream and downstream from the point where chemicals were added in a 12,000-ft, 20-in. main leading from the plant. Caustic soda had reduced corrosion 12 to 26 percent but did not provide enough protec-tion at distant parts of the system. Zinc orthophosphate, at a dosage of 1.5 mg/L for the first 5 days and 0.2 to 0.5 mg/L thereafter, was fed as a liquid solution of zinc sulfate and phosphoric acid, forming a more tenacious protective film of zinc phosphate precip-itate. Although zinc orthophosphate was more economical than treatment with caustic soda, its use had to be discontinued because it caused algal blooms in a reservoir.

Zinc orthophosphate has also been effective in protecting asbestos cement pipes with a zinc dosage of 0.3 mg/L.[126] A protective coating was formed by attaining and maintaining zinc-hydroxycarbonate saturation. Monitoring of zinc levels at extremities in the distribution system insured that concentrations were high enough for precipitation to occur.

Zinc orthophosphate solution is acidic and should be stored in a fiberglass or lined tank with corrosion-resistant materials used for pipes, valves, pumps, and fittings. The chemical dose can be adjusted if necessary, based on monitoring zinc concentrations at various points in the distribution system.

Monitoring Techniques

Any corrosion control method should be monitored to measure its effectiveness. This can be done several ways, including placing test coupons in the distribution system, using an in-line or linear polarization device, sampling and analyzing tap water, or examining water for extent of staining.

Test Coupons

Test coupons can be placed at various points in the distribution system to assess corrosion rates. Test specimens meeting American Iron and Steel Institute specifications can be obtained from coupon suppliers. The National Association of Corrosion Engineers (NACE) has standards for coupon testing in the laboratory.[127] The coupons are weighed before and after exposure. Exposure time varies from 1 to 4 months. The penetration in mils (.001 in.) per year is calculated as follows:

$$\text{mils/yr} = \frac{(\text{weight loss in mg})(534)}{(\text{area in sq in.})(\text{time in hrs})(\text{metal density in g/cm}^3)}$$

Other methods of analyzing coupons include visual inspection for type of corrosion and presence or absence of a protective film.

[125]G. M., Haskew, "Use of Zinc Orthophosphate Corrosion Inhibitor--Plant Practice," *AWWA Seminar Proceedings, Controlling Corrosion Within Water Systems*, Atlantic City, NJ (June 25, 1978), p 2.
[126]Shock and Buelow, p 645.
[127]*Test Method for Laboratory Corrosion Testing of Metals for the Process Industries*, NACE Standard TM-01-69, NACE, Houston, TX (1969).

In-Line Test Device

The Illinois State Water Survey developed a corrosion test specimen holder which was adopted as ASTM Standard D2688.[128] The advantage of the in-line tester over test coupons is that the test pipe section is exposed to the same velocity profile as the rest of the pipe in the distribution system. The device holds a test pipe insert in a metal cylinder with a polyvinyl chloride (PVC) sleeve and spacers. The inserts could be prepared at the installation using a lathe to reduce the external pipe diameter, usually to 1.125 in. The original weight of the specimen should be about 100 grams. Epoxy paint is applied to the surface and ends of the insert before exposure to protect the exterior from corrosion. The exposure is usually 2 to 4 months (longer for specimens closer to the treatment plant). After exposure, the exterior of the specimen is cleaned and weight loss is determined.

The corrosion rate is expressed as milligrams per square decimeter per day (mdd) or as inches of penetration per year (ipy). The mdd is calculated by dividing weight loss by interior surface area of the pipe. To convert to ipy, multiply mdd by the quantity 0.00144/(density of pipe). Corrosion is also expressed as mils/yr as previously defined. The 1962 AWWA water quality goals are for a weight loss of 5 mg/cm^2 for a 90-day test period of a galvanized specimen, which is 1.1 mil/year or 0.0011 ipy.[129]

Linear Polarization

The test specimen corrosion rate can be measured in the lab instantly using a linear polarization technique.[130] A very small current is applied to submerged test specimens and the change in potential is measured against a reference electrode. The change in potential per unit of applied current density correlates with specimen weight loss. Such a device typically costs about $2000 to $2500.[131] A monitoring program using coupons or pipe inserts would probably be less costly, simpler to use, and more accurate.

Tap Sampling

Taking water samples from consumers' taps is another way to determine the extent of corrosion in the distribution system. Depending on the composition of the pipes, materials such as lead, copper, iron, zinc, cadmium, and asbestos may be leached into drinking water. The USEPA has established maximum contaminant levels for lead and cadmium in the Primary Drinking Water Regulations, and for iron, copper, and zinc in the Secondary Drinking Water Regulations. Sampling and analysis over time would determine if the water complies with the regulations and if pipe deterioration due to corrosion may be progressing. Table 21 shows suggested parameters to analyze for distribution systems of various compositions.

Staining Indication

Effectiveness of treatment may also be assessed by discharging treated water into a white porcelain plate and checking for staining. This test is not an accurate indicator, however, because corrosion products may be forming tubercules on the pipe surface,

[128] Larson.
[129] Mullen, p 290.
[130] Larson, p 13.
[131] Chester Neff, Illinois State Water Survey, Personal Communication, May 4, 1984.

has 90 percent moisture. When filled to a depth of 3 to 5 ft, it should consolidate to 6 to 10 in.[168]

The sludge will not compact as easily (probably not to more than 30 to 40 percent solids) if it is always submerged in the lagoon. The water level should be kept low.[169]

Three lagoons could be used in turn, each holding 1 year's production of wet sludge. When sludge has reached 50 percent consolidation, that lagoon would be removed from service and the next placed in service.[170]

Municipal and Army water treatment plants have used polymers to make the sludge more dewaterable. The polymer is added at the discharge from the sludge holding tank by a feed pump. It helps keep the sludge porous so water can drain from it. As the sludge dries and begins to cake, it is ready for removal. More information about types of polymers and polymer feed systems is found in Chapter 5.

Sand Drying Beds

Sand drying beds need a large land area with sand and gravel layers to collect filtrate. The sludge is spread in 1 to 2 ft layers.

Pilot studies on mixed coagulation/softening sludges applied at 0.4 lb/sq ft-day produced a cake with a solids content of 50 percent.[171]

Polymers may be added to the sludge to prevent seepage into the sand and gravel and to enhance evaporation. This can reduce drying time by 50 to 70 percent.[172]

Softening sludges usually drain rapidly, iron coagulant sludges moderately well, and alum sludges (without polymer addition) drain poorly.[173]

Freezing

Freezing is a physical conditioning method to dewater sludge and improve filterability. Sludge is first thickened to a 2 to 4 percent solids content.[174]

Freezing may be done naturally by spreading sludge in thin layers in drying beds, or artificially by using refrigerant within coils submerged in a sludge vat. It is a batch process of freeze-thaw cycles.

Freezing is more effective for alum sludges than softening sludges. The aluminum hydroxide contains chemically bound water which is released during the freeze-thaw cycles. The resulting material is granular and does not reabsorb water; the effect is irreversible.

[168]Howson, p 192.
[169]Howson, p 192.
[170]Howson, p 192.
[171]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," Committee Report, *JAWWA*, Vol. 70 (1978), p 603.
[172]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 549.
[173]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 549.
[174]J. H. Wilhelm, "Freeze Treatment of Alum Sludge," *JAWWA*, Vol. 68 (1976), p 313.

Table 25

Estimated Sludge Disposal Costs

(Based on 1 mgd plant using lime, alum and powdered activated carbon)

	Process Cost per mgd 1980 Dollars*
Lagoon	20
Surge tank + gravity thickener + sand bed	44
Surge tank + gravity thickener + filter press	92
Surge tank + basket centrifuge	67
Surge tank + decanter centrifuge	39
Surge tank + vacuum filter	86
Surge tank + belt filter press	109

Note: To estimate hauling costs (5 miles at 20 percent concentration) add $10 per mgd.

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*Reprinted from *Journal AWWA*, Vol. 76, No. 4 (April 1984), A. H. Vicory, "Controlling Discharges of Water Plant Wastes to the Ohio River," p 125, by permission. Copyright © 1984, The American Water Works Assocation.

Lagoons

Lagoons are a very common treatment for dewatering sludge; an AWWA survey showed that 56 percent of water treatment plants with softening used them.[166] Of those utilities with lagoons, 60 percent used the lagoons for permanent sludge disposal; 32 percent used them to thicken sludge to 30 to 60 percent solids before dredging it to spread on farmland or mix with landfill; and 8 percent used the lagoons for dewatering, with dried cake being applied to farmland.

A long, narrow shape is preferable for a lagoon, with sludge inflow at one end and clear water discharge at the other. Three to five acres would be needed for each mgd of plant capacity.[167]

Softening sludge should be dewatered to 50 percent moisture in the lagoon. It is easier to handle, compacts better, and occupies 16 percent as much volume as when it

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[166] "Lime Softening Sludge Treatment and Disposal," p 606.
[167] L. R. Howson, "Sludge Disposal," *Water Treatment Plant Design* (Ann Arbor Science, 1979), p 192.

Summary of Sludge Dewatering and Thickening Methods

	Dewatering (D) or Thickening (T)	% of Solids in Thickened Sludge	Other Treatment Needed	Amount Operator Attention Needed	Polymers Needed	Relative Cost	Comments
Lagoons	T or D	50%	Could be followed by dewatering.	Low	Optional to improve dewatering.	Low	Softening sludges dewater more easily.
Sand Drying Beds	T or D	50%	Could be pre-thickened or followed by dewatering.	Low	Optional to improve seepage, evaporation.	Low	(See lagoons)
Freezing	D	20% after filtering, 70% after draining.	Thicken first to 2 to 4% solids. Dewater or filter afterward.	Medium	No	Medium	More effective for alum sludges.
Belt Press	D	12-20% alum sludge, 40% softening sludge.	Prethicken	High	Optional	Very high	New application for water treatment plants.
Filter Press	D	40-60% alum sludge.	Prethicken	High	Optional to improve dewatering.	High	Usually not economical for small plants.
Centrifuge	D and T	12-20% alum sludge, 40-70% lime sludge.	Prethicken	High	No	Medium	Softening sludges more effectively dewatered. Solid bowl more effective for alum sludge.
Vacuum filtration	D and T	15-17% alum sludge alone, 30-40% with lime, 40-70% lime sludges.	Prethicken	High	Yes, especially for alum sludge.	High	More effective if sludge has high Ca:Mg ratio.
Pressure filtration	D and T	50%	Prethicken	High	Yes, or other conditioners, especially for alum sludge.	High	Effective even for sludge with low solids content.

Table 23

Processes Related to Sludge Handling and Key O&M Criteria

	Treatment Understanding	Process Monitoring and Control	Preventive Maintenance	Analytical Capabilities
Chemical Dosage	x	x		x
Coagulation/ Flocculation		x		
Clarification		x		
Filtering	x	x	x	
Softening	x	x	x	x

Control the solids withdrawal from the clarifier to increase the solids content of the sludge. Increasing the solids content of the sludge 2 to 5 percent will decrease the volume by 60 percent.[164]

Use split treatment, which can help reduce the solids since less water is treated (because of the bypass) and solids from recarbonation are eliminated.

Recycle a portion of the sludge to improve coagulation and reduce the amount of lime and soda ash needed. This in turn can reduce sludge volume. (Sludge recycling is discussed in Chapter 5.)

Use polymers as the primary coagulant or as a coagulant aid with metallic ion coagulants. This works best for sludges high in aluminum hydroxide. Alum sludge is one of the most difficult types of sludge to dewater. A polymer reduces the amount of bound water in the sludge, thereby reducing sludge volume.[165] (Use of polymers as coagulants and coagulant aids is discussed in Chapter 5.)

Dewatering and Thickening the Solids

There are a number of ways to dewater and thicken sludge, ranging from simple reliance on gravity such as in a lagoon to more costly mechanical devices such as filters or centrifuges. The techniques discussed in this section are summarized in Table 24. Table 25 shows 1980 cost estimates for various combinations of these treatments for a plant using lime, alum, and powdered activated carbon.

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[164]"Lime Softening Sludge Treatment and Disposal," p 602.
[165]"Water Treatment Plant Sludges--An Update of the State of the Art, Part 1," p 501.

Ca = Calcium hardness removed as $CaCO_3$, mg/L

Mg = Magnesium hardness removed as $CaCO_3$, mg/L

Al = Alum dose as 17.1 percent Al_2O_3, mg/L

Fe = Iron dose as Fe, mg/L

SS = Raw water suspended solids, mg/L

A = Additional chemicals, mg/L (polymer, clay, activated carbon, etc.)

This equation shows that the SS content and the amount of coagulant and coagulant aid have a direct impact on the amount of sludge produced.

Approach to Handling and Treating Solid Wastes

The approach to handling and treating water treatment plant solid wastes is fourfold:

● Reduce the amount of solids produced

● Dewater and thicken the sludge (solids)

● Dispose of the solids

● Treat the supernatant.

The most important factors are to reduce the amount of sludge generated and to make the sludge easier to dewater, which can be done by altering or improving some of the existing treatment processes. The processes that most influence sludge production and handling are shown in Table 23. Ways of reducing sludge generation and improving dewaterability are discussed below.

Reducing the Amount of Solids Produced

Make sure the chemicals for coagulation and softening are added in the proper dosage and are well mixed in flash mixers and flocculators. If the dose is too high, more sludge is produced and chemicals are wasted. If mixing is ineffective, the coagulant dose will be higher than necessary and too much sludge will be produced.

Consider using sodium hydroxide (NaOH) in place of soda ash and some of the lime in softening; this can reduce the solids produced by 50 percent.[163] The advantage of this significant reduction would have to be weighed against the higher cost of NaOH compared to soda ash and lime, however.

Remove less hardness from the raw water, if possible. This will mean fewer solids will be produced and fewer chemicals will be needed.

Remove less magnesium hardness from the water, if possible. Less magnesium will make the sludge easier to dewater.

[163]"Lime Softening Sludge Treatment and Disposal," p 601.

Table 22

Water Treatment Plant Waste Volumes and Characteristics

Coagulation (Turbidity Removal) Sludge		Reference
sludge volume as % of raw water treated	< 1.0	a
solids content	0.1 - 3.5%	a
suspended solids concentration	100 - 1000 mg/L	b
solids content after long-term settling	10%	c
	4-36%	d

Softening Sludge		
200 ppm dry sludge produced per 100 ppm hardness removed		e
2-1/2 lb sludge/1 lb lime used		f
solids content of settled sludge	2-30%	a
Ca:Mg ratio > 5	easily dewatered	g
Ca:Mg ratio < 2	difficult to dewater	g

Filter Backwash Wastewater		
wastewater volume as % of filtered water volume	1-5	g

a   Committee Report (1978), AWWA, p 500.
b   J. W. Clark, (1977), p 640.
c   *The Quest for Pure Water*, AWWA, p 205.
d   D. C. Calkins, p 424.
e   *Water Treatment Plant Design*, AWWA (1971).
f   L. R. Howson, p 185.
g   Committee Report (1981), p 600.

8 SLUDGE

Background and Regulations

Environmental controls established in the past 12 years have made sludge disposal a significant problem for municipal and Army water treatment plants. Sludge is generated as a result of turbidity removal, softening, and filter cleaning. Softening sludge can amount to 5 percent of the volume of raw water treated, sludge from clarification can amount to 1 percent, and backwash water from filter cleaning can amount to up to 5 percent of the raw water volume.[158] So, even at small Army plants the volume of wastes can be significant. These wastes were once discharged directly to surface water or sewers, but now in most cases they must be treated.

The Water Pollution Control Act Amendment of 1972 (PL 92-500) classified sludge from water treatment plants in the industrial category, which means treatment must be the "best control technology currently available" and should be consistent with the national goal of zero discharge of pollutants. In keeping with the zero discharge goal, sludge is usually dewatered and the supernatant may be recycled.

Sludge solids are classified as a solid waste under the 1976 Resource Conservation and Recovery Act (PL 94-580) and must be properly disposed of or recycled, such as by reclaiming the lime or alum or applying it to agricultural land. In India, sludge is recovered from settling basins, dried, and used as a source of clay for bricks.[159] In Japan, alum recovery was practiced at 15 water treatment plants constructed after World War II.[160] Although the technology for recovering lime and alum from sludge has been known since the early 20th century, facilities were not installed at treatment plants until after the 1950s,[161] and these have been larger water treatment plants where the investment is more easily justified economically.

Solids Production and Characteristics

Table 22 shows ranges of volumes and solids content for sludges produced from turbidity removal, softening, and filter backwash. Volume and solids content varies from one water source to another, but these values can be used for a rough comparison with an existing plant or to estimate sludge produced from a new plant or process. An equation has been developed[162] to calculate the dry weight of solids produced in lb/day from softening and turbidity removal:

$$S = 7.97 \ Q \ (2 \ Ca + 2.6 \ Mg + 0.44 \ Al + 1.9 \ Fe + SS + A)$$

where: S = Sludge solids (dry weight), lb/day
         Q = Plant flow, mgd

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[158]"Water Treatment Plant Sludges—An Update of the State of the Art: Part 1," Committee Report, *JAWWA*, Vol. 70 (1978), p 500.

[159]H. E. Hudson, "Water Treatment Present, Near Future Futuristic," *JAWWA*, Vol. 68 (1976), p 277.

[160]"The Quest for Pure Water," Vol. II, *AWWA* (1981), p 203.

[161]"The Quest for Pure Water," pp 211 and 215.

[162]"Lime Softening Sludge Treatment and Disposal," Committee Report, *JAWWA*, Vol. 73 (1981), p 600.

Mode of Operation--General Improvements

The most important O&M criteria for filtration are treatment understanding, process monitoring, and control and preventive maintenance (Table 3). These criteria are addressed in the general operational improvements listed below.

● Improve the quality of water applied to the filters. If the water is too turbid, the filters will require backwashing too frequently, wasting water and energy.

● Avoid frequent filter startups, shutdowns, or sudden rate changes. Sudden increases in filter rates can flush trapped material through the sand. Rates should be increased gradually, over a period of 10 minutes.[155] Frequent startups or shutdowns can allow gas bubbles to be trapped in the sand, increasing the flow rate in other portions of the bed. During backwashing, the air bubbles will rise to the surface and disrupt the media.

● Avoid development of negative head (pressure below atmospheric) in the filter. Dissolved gases in the water will cause air bubbles which may block the normal flow through the media. (Air bubbles will rise to the surface during backwashing.) Negative head can be avoided by maintaining a high water level above the filter and limiting terminal headloss to the sum of the clean filter headloss (ft) plus the normal depth above the media.[156]

● Maintain the filter rate control mechanisms properly to avoid sudden changes in the filter rate.

● Make treatment plant operators aware of the above problems so they can prevent them or take corrective actions.

● Inspect the filter media regularly for surface cracking, mudball formation, mounding, and bed shrinkage.

● Make sure flocculation intensity is not too high or flocculation is not too long, so the floc particles will not break up and lead to filter breakthrough.

● Add a polymer during the coagulation/flocculation stage or after settling to help produce a stronger floc which can resist shearing when subjected to hydraulic forces in the bed, especially during rate changes.

● Consider using nonionic polymers as filter aids at a dosage of 0.1 to 1.0 ppm to enable higher filtration rates while preventing filter breakthrough. Terminal headloss may be higher when the polymer is used.[157]

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[155]Cleasby, "Improving Filter Performance," p 38.
[156]Cleasby, "Improving Filter Performance," p 38.
[157]Cleasby, "Improving Filter Performance," p 36.

Direct Filtration

Direct filtration is where water is applied directly to the filters after flocculation. There is no clarifier. It is feasible at plants where raw water turbidity and color are low (both preferably less than 25 units), where color is low and maximum turbidity is less than 200, or where turbidity is low and color is less than 100 units.[149] Other researchers have found that high rate direct filtration was viable if the alum dose was less than 12 mg/L.[150] At some direct filtration plants with raw water turbidity below 5 Turbidity Units (TU), solids removal was 97 percent, compared to 2 percent removal in conventional sedimentation.[151] In general, direct filtration would work where sludge production is not excessive and sludge could be trapped by the filter without sedimentation.

Filtration rates are the same as for conventional filters, or higher if a filter aid is used. (A filter aid is a substance added to the water to improve filter performance.) At a pilot plant in Ontario, Canada, the rate of the direct filters was increased from 2.4 to 4.8 gpm/sq ft by using a mixed media filter and a filter aid.[152] The dose of the filter aid was increased during periods of high water turbidity. Also, the water was sampled at a point between the filter layers and if turbidity was high, the filter aid dose was increased before the end of the run to prevent turbidity breakthrough. Others have reported filtration rates of 5 to 10 gpm/sq ft if the raw water turbidity was less than 5 TU.[153]

Direct filtration requires more operator attention in making adjustments such as changing coagulant or filter aid dose or initiating a backwash, and in being alert for signs of problems. Since the detention time in the clarifier is eliminated, the filters are more subject to sudden operational changes.

Considerations for direct filtration are:

● Conventional plants could be retrofitted by converting a clarifier and existing filters to a high rate direct filter.

● Pilot studies should be done to determine the appropriate sizing of filter media. The optimum effective size coal for the Ontario plant mentioned above was 1.1 mm.[154]

● Key design and operating parameters are: raw water color and turbidity, sludge production, coagulant dose, presence of algae in the raw water, flocculation time and intensity, coagulant and filter aid dosage, floc strength, effective size of filter media, filtration rate.

● The filters are more subject to sudden operational changes or changes in raw water quality and this requires operator alertness.

● Some states (for example, Utah) require that the water receive complete treatment (coagulation, flocculation, filtration, chorination). If so, states may not approve direct filtration.
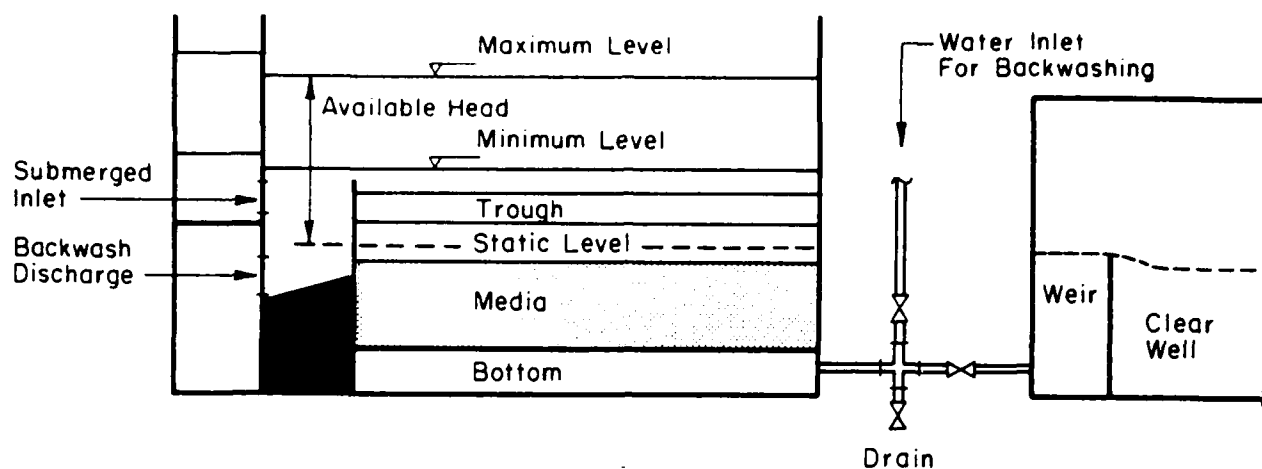
[149] Bowers, p 86.
[150] W. R. Hutchinson, "High-Rate Direct Filtration," *JAWWA*, Vol. 68 (1976), p 297.
[151] Bowers, p 86.
[152] Hutchinson, p 297.
[153] Bowers, p 86.
[154] Hutchinson, p 297.

Figure 13. Typical arrangement for declining rate filter system showing normal minimum and maximum operating levels. (Reprinted from *AWWA Seminar Proceedings, Upgrading Water Treatment Plants to Improve Water Quality*, J. L. Cleasby, "Declining Rate Filtration," Atlanta, GA, June 15, 1980, by permission. Copyright © 1980, The American Water Works Association.)

A pilot plant study in Ames, Iowa, showed that filter runs were one-third longer and water quality was better with declining rate filters.[147] Other studies have shown similar results.[148]

Advantages of declining rate filters are:

● Filter runs are longer with better water quality.

● There is a smooth transition in loading while one filter is taken out of service for backwashing.

● No headloss gauges are needed since backwashing is initiated based on water level.

● No effluent rate controllers are needed.

● Better water quality is maintained toward the end of the run.

● Negative head is prevented because the media are always submerged.

[147]J. L. Cleasby, "Declining Rate Filtration," *AWWA Seminar Proceedings, Upgrading Existing Water Treatment Plants to Improve Water Quality*, Atlanta, GA (June 15, 1980), p 103.
[148]Prendiville, p 67.

Type of Filter Media

Dual Media Filters

Traditionally, filter media have consisted of 24 to 30 in. of sand placed over a 6 to 18 in. gravel layer containing the underdrain pipes.[141] The filtration rate is 2 gpm/sq ft.[142] Higher filtration rates are now achieved by switching to dual media filters that have a 6 to 16 in. layer of 0.45 to 0.5 mm effective-size sand. (Effective size is the diameter of sand grain below which 10 percent of the sample is finer.) Above this is a 12 to 24 in. layer of anthracite coal. The zone of intermixing of sand and anthracite is usually from 1 to 6 in. thick[143,144] and the intermixing zone should not create an impermeable layer. The supportive gravel layer is the same as in conventional filters.

Filters at one Army water treatment plant were converted to dual media and the overflow rate was increased from 2 to 4 gpm/sq ft. The total plant capacity was increased from 10 to 15 mgd. At a San Diego, California, water treatment plant where filters were converted to dual media by replacing 18 to 20 in. of sand with anthracite, the individual filter capacity increased from 15 to 20 mgd.[145]

Some utilities have tried mixed media filters, a more sophisticated version of dual media filters. This type has two layers of sand--one of intermediate fineness and one of higher density such as granite--below the anthracite layer. Studies of mixed media filters have shown that filter runs may be longer than the dual media type and iron removal was better, but the difference in finished water turbidity was negligible.[146]

Declining Rate Filters

Most filters are operated at a constant rate with rate controllers at the effluent. As filters get dirty the rate controllers open effluent valves to keep the flow constant. Backwash is initiated when headloss reaches a certain level.

Declining rate filters (Figure 13) are simpler in operation and offer many advantages over the constant rate type. A common header distributes the water so the filters all have nearly the same water level. No effluent rate controllers are necessary; instead, the outlet discharges over a weir to a clearwell, so the filter media will always be submerged, avoiding negative head. The difference between the top of the effluent weir and the height of the water above the filter media provides the driving force through the filters. As one filter gets dirty, flow automatically shifts to the other filters. Because of the common header, the cleanest filter has the highest flow. Backwashing occurs when water level rises to a predetermined level. While one filter is removed from service for cleaning, the other filters handle the extra load.

[141] Weber, p 163.
[142] "Water Quality and Treatment," p 245.
[143] "Water Quality and Treatment," p 254.
[144] Weber, p 169.
[145] Snow, Water Treatment Staff, San Diego, CA, Personal Communication, May 1984.
[146] Upgrading Study--Potomac Water Filtration Plant, pp 4-12.

Another method of air scouring involves allowing the water level to drop almost to the level of the media surface and then air scouring for 3 to 5 minutes.[139] With the air still on, backwashing is begun at a lower rate. The air is turned off when the wash water level reaches about 8 in. below the troughs. Then the backwash is continued at the normal rate.

Filter Backwash Problems

Problems in the filters caused by ineffective backwashing are: mudballs, surface cracking, areas of "boiling water" during backwash, mounding of the filter media, air bubbles rising to the surface during backwash, nonuniform gradation of the media, premature filter breakthrough, or approaching terminal headloss too soon.

Mudballs form when the backwash rate is too low or there is not enough agitation to break up accumulated solids on the filter surface. While the bed is fluidized they will sink to the bottom of the filter or, in dual media filters, rest between the layers. The result is ineffective filter areas which will cause nonuniform flow, short circuiting, and filter breakthrough. The bed surface should be checked for mudballs, or a special sampler can be used to check for mudballs up to 6 in. below the surface.

Mudballs tend to sink deeper in an anthracite medium so a sample should be taken after draining the water to about 12 in. below the sand surface. The mudballs remain on a 10 mesh seive after rinsing the sand through. Their volume is measured by dropping them into a graduated cylinder of water and reading the change in volume. If the mudballs' volume exceeds 0.2 percent of the volume of the media sample, backwash facilities should be improved.[140] If mudballing below the surface is excessive, the filter media must be replaced.

Surface cracks develop when the bed shrinks as headloss increases during filter operation. This can also result in filter breakthrough. The shrinking occurs if inadequate backwashing has left a compressible coating on sand grains. The coating can also be removed by improving surface washing.

Some filter problems are noticeable during filter backwash. Air bubbles rising to the surface, mounding of the media, and boiling areas of sand or a nonuniform surface after backwash is finished indicate portions of the filter are not being cleaned adequately. The media should be probed during backwashing and while the filter is at rest to determine if it has been disturbed and needs regrading.

Another approach is to check the backwash rate and the backwash water jets. If the backwash rate is too high, the media gradation can be disturbed. If it is too low, mudballs, clogging, and surface cracks will result. The backwash pump could be modified to deliver more water, or the existing plumbing could be adequate if the filter is switched to dual media.

[139]Cleasby, "Improving Filter Performance," p 41.
[140]"Water Quality and Treatment," p 27.

7 FILTRATION

In conventional treatment, filtration follows the coagulation, flocculation, and sedimentation processes to remove fine suspended material to produce a high quality effluent. Filtration plays an important role in removing contaminants including THMs, iron, and manganese. Filtered material is a source of treatment plant solid wastes. A properly designed and operated filtration system affects not only the overall character of the treated water, but also the amount of waste solids produced and treatment plant O&M costs.

Aspects of filter design and operation which could contribute to improving performance are backwashing procedures, type of filter media, mode of operation, and configuration in the treatment plant, e.g., direct filtration. These topics are discussed in the following sections.

Backwashing Procedures

General

Normal backwashing involves expanding the filter medium by 15 to 30 percent of its normal depth. For a dual media filter, the depth should be expanded to 3.3 ft above normal in order to stratify the layers.[133] The backwash rate is usually 15 gpm/sq ft for 3 to 4 minutes.[134] The backwash water valve should be opened slowly, by having a speed controller on the valve operator or by hydraulically or electrically controlling the washwater valve. There should be 30 seconds between the time the valve is first opened and when full flow is reached.[135]

During backwash the filter media is fluidized, but there is often not enough abrasion between grains of media to effectively clean them. Surface washing and/or air scouring can help accomplish this.

The surface wash is usually turned on 1 or 2 minutes before backwashing begins and turned off 1 to 2 minutes before it ends.[136] Jets of water move through the fluidized bed and clean the grains. Sometimes filter media are lost over the wash troughs during backwashing but this can be avoided if the water jets are fully submerged.

Air scouring has been used in Europe. Separate piping is needed to deliver 3 to 5 cubic feet per minute (cfm) of air to a point between the gravel and media layers. The media is still submerged during the air scour, which lasts 2 to 3 minutes.[137] It is immediately followed by normal backwash, and the dislodged particles are washed out. The air scour aids in cleaning the media while preventing the gravel from shifting and requires less water for backwash.[138]

[133] Prendiville, p 67.
[134] "Water Quality and Treatment," p 261.
[135] "Water Quality and Treatment," p 261.
[136] J. L. Cleasby, "Improving Filter Performance," *AWWA Seminar Proceedings, Upgrading Existing Water Treatment Plants to Improve Water Quality*, Atlanta, GA (June 15, 1980), p 40.
[137] Weber, p 175.
[138] Weber, p 175.

Table 21

Water Characteristics of Interest for Various Water
Main Materials*

Water Main Material	Water Characteristics of Interest
Ductile and cast iron	Color, conductivity, dissolved, iron, manganese, pH (and alkalinity and calcium if main is cement-lined)
Steel	Color, conductivity, dissolved oxygen, iron, manganese, pH
Concrete cylinder	Alkalinity, calcium, conductivity, pH
Asbestos-cement	Asbestos fibers, iron silica
Galvanized steel	Alkalinity, cadmium, color, conductivity, dissolved oxygen, iron lead, pH, zinc

eventually leading to increased surface roughness and loss of carrying capacity. This check should be used in conjunction with other tests.

Miscellaneous Methods

Other ways of monitoring for corrosion are to inspect interior pipe surfaces for tuberculation or presence of a protective film when a repair or new connection is made, to keep logs of pipe repairs and hydraulic characteristics to detect whether conditions are stabilizing or deteriorating further, and to keep track of complaints from customers (their location in the distribution system, the season, and flow condition).

If pipe sections can be examined, they should be checked for the type of corrosion, presence of protective film, pitting potential, and any deposits. Using a microscope to measure width and depth of pits due to corrosion over a given time will help estimate pipe service life for certain water conditions. Chemical analysis of any scale or protective film may help determine the mechanism by which corrosion is being prevented or is progressing. An electron microscope analysis may be useful, particularly to determine if the matrix of asbestos cement pipe has deteriorated and exposed asbestos fibers.[132]

Records should be kept of pipe rupture or repairs and inspections, coupon monitoring, and sampling. Correlating these observations and analyses with water conditions and treatment practices can do a great deal to help solve corrosion problems.

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[132]Kirmeyer, p 81.

Studies have shown that the freeze temperature and thawing time are not as important as the time allowed for sludge to freeze and the time the sludge was held in the frozen state. It is necessary to completely freeze the sludge.[175]

Treated sludge may be dewatered in lagoons or drying beds or filtered in a vacuum filter. At a water treatment plant in England, the solids were drained to 60 to 70 percent solids by weight.[176] Studies comparing solids content of settled sludge before and after freeze treatment have shown about 2 percent solids content by weight before freezing and about 20 percent solids after freezing.[177]

Belt Press Dewatering

This technique compresses sludge as it travels between two belts moving in the same direction at the same speed. The filtrate seeps through the lower belt and the sludge is collected at the end of the belt. Belt press dewatering has been used in Europe for the past 20 years for dewatering sewage sludge,[178] but is a relatively new application for water treatment plant sludge. It can produce a filter cake with 12 to 20 percent solids by weight for alum sludge and up to 40 percent solids by weight for lime softening sludge.[179]

Filter Press Dewatering

In this technique, the sludge is placed on filter cloth held over plates in a frame. The plates are compressed and filtrate seeps down. When the plates are separated the cake falls off (Figure 14). Filter press dewatering is not usually economically justifiable unless the treatment plant capacity is at least 40 mgd.[180]

Alum sludge can be concentrated to 40 to 60 percent solids.[181]

Lime or polymer may be added to the sludge as a conditioning agent to improve dewatering effectiveness with the filter press.

Centrifugation

This process relies on centrifugal acceleration to separate solids. The greater the difference in density between the solids and the liquid phases, the better the thickening. The residence time in the centrifuge should be long enough to allow solids to compress, yielding a higher solids concentration in the cake.

There are two types of centrifuges: solid bowl and basket type, with the solid bowl dewatering alum sludges better.[182] Figure 15 shows a horizontal solid bowl centrifuge.

It is better to operate the centrifuge at a lower bowl speed to conserve power and reduce wear and maintenance. The lower speed will also require a lower polymer

[175]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 548.
[176]Wilhelm, p 313.
[177]Wilhelm, p 314.
[178]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 604.
[179]"The Quest for Pure Water," p 210.
[180]"The Quest for Pure Water," p 209.
[181]"The Quest for Pure Water," p 210.
[182]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 549.
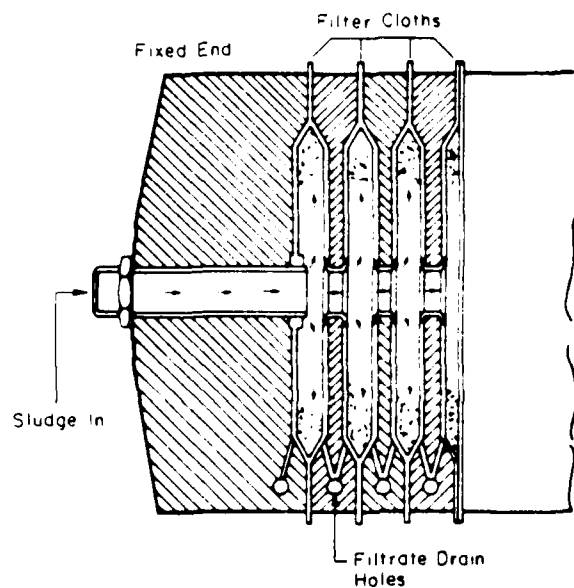
Figure 14. Sludge filter press. (Reprinted with permission from *Public Works Magazine*, Vol. II, AWWA, 1981, "The Quest for Pure Water," p 208.)
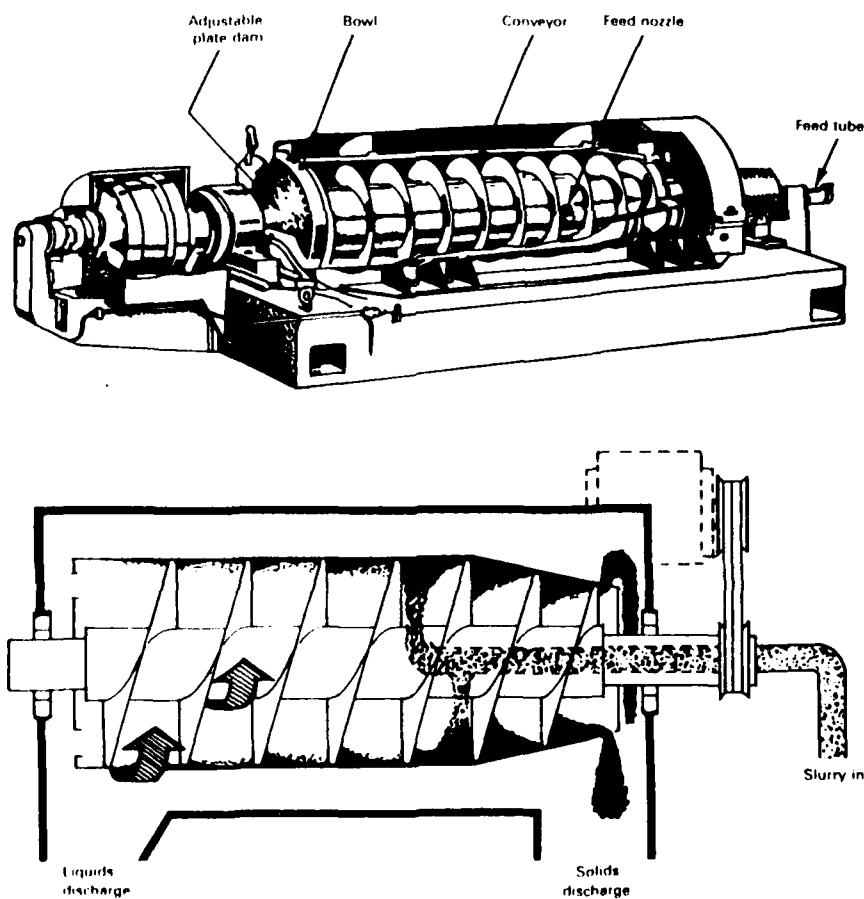
Figure 15. Solid bowl centrifuge. (Reprinted with permission from Sharples-Stokes Division, Pennwalt Corporation, J. W. Clark, *Water Supply and Pollution Control*, Dun-Donnelley, NY, 1977.)

dose.[184] Tests have shown that the cake is drier and polymer doses are lower if the centrifuge is operated at 75 to 86 percent capacity and the solids concentration of the feed is uniform.[184]

Softening sludges are more easily dewatered than coagulation sludges. Lime softening sludges can be thickened to a 40 percent solids concentration[185] while some plants have had 55 to 70 percent solids using a bowl type centrifuge.[186] Alum sludges can be dewatered to a cake solids concentration of 12 to 20 percent.[187] The feed typically has a solids content of less than 1[188] to 25 percent and the centrate has a solids content in the range of 1.0 to 1.5 percent.[189]

If the Ca:Mg ratio of the sludge is high (above 5) the solids content of the cake will be about one-third higher than if the Ca:Mg ratio is low (close to 1).[190]

Vacuum Filtration

A drum with filter cloth stretched over it rotates through the sludge in this method (Figure 16). A pressure differential across the sludge causes the sludge to thicken on the outside of the drum and filtrate to pass to the inside. The angular speed of the drum is usually 0.2 to 0.5 rpm with a vacuum of 15 to 25 in. Hg.[191]

Filter medium selection is important to avoid blinding of the medium. An example is polypropylene monofilament belt medium, rated at an airflow of 300 cfm/sq ft at 15 in. Hg with a loading of 1.4 lb/sq ft hr.[192]

Vacuum filters could be a traveling medium type with a moving belt that continually removes the medium from the drum and washes it with a high pressure spray, or a precoat medium filter which is shaved off in small increments (0.005 in.) while the drum slowly rotates.[193] Precoat medium filters are usually used with coagulation sludges. Traveling medium filters usually require a filtration aid such as polymer, lime, or both.

This method works better on lime softening sludge or combined softening-coagulation sludge than coagulation sludges.[194,195] A filter cake with a 40 to 70 percent suspended solids content can be produced from lime softening sludge. Filter loadings range up to 90 lb/sq ft-hr with a feed solids concentration of 5 to 30 percent and a filtrate solids concentration of 0.1 to 0.15 percent.[196] The solids content of long-term settled sludge can indicate the cake solids content achievable by vacuum filtration.

[183]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 549.
[184]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 549.
[185]*The Quest for Pure Water*, p 210.
[186]"Lime Softening Sludge Treatment and Disposal," p 603.
[187]*The Quest for Pure Water*, p 210.
[188]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 549.
[189]"Lime Softening Sludge Treatment and Disposal," p 603.
[190]"Lime Softening Sludge Treatment and Disposal," p 607.
[191]"Lime Softening Sludge Treatment and Disposal," p 604.
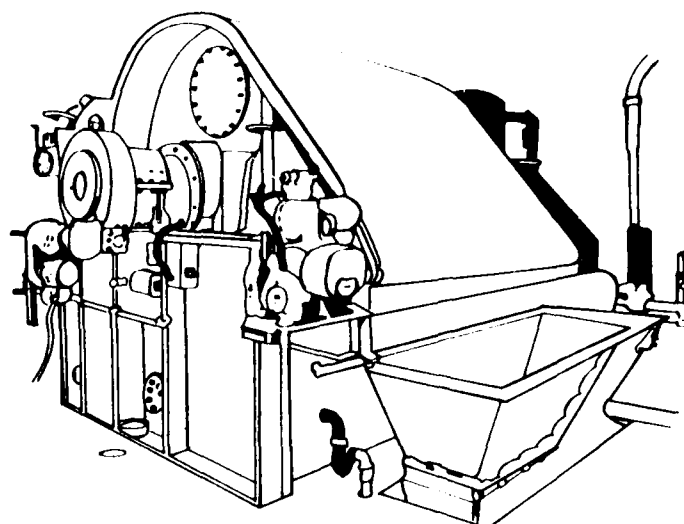[192]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 551.
[193]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 551.
[194]"Lime Softening Sludge Treatment and Disposal," p 604.
[195]D. C. Calkins, "Characterization of Chemical Sludges," *JAWWA*, Vol. 65 (1973), p 427.
[196]"Lime Softening Sludge Treatment and Disposal," p 604.

Figure 16. Vacuum filter. (Reprinted with permission from *Water Supply and Sewerage*, 1979, E. W. Steel, T. J. McGhee, courtesy of Envirex, Inc., a Rexnord Company.)

Alum sludges can achieve cake solids concentration of 15 to 17 percent when a polymer conditioner is used and 30 to 40 percent if a lime conditioner is used.[197]

Based on plant operating experience, the solids content of the filter cake is much higher if the plants have sludge with a Ca:Mg ratio above 5, compared to plants with a ratio below 1.[198] The magnesium content does not affect how easily the sludge is filtered; it does affect the solids content achievable in the filter cake.[199]

Filter backwash generally does not filter well because it usually contains few softening residues and has a low solids content.[200]

Filterability is measured in terms of specific resistance. In general, sludges with a specific resistance below 10×10^7 sec^2/g filter well and those with a specific resistance above 50×10^7 sec^2/g filter poorly.[201]

Pressure Filtration

This technique stretches the filter medium over porous plates held in a frame. The capacity of the pressure filter depends on the number and size of the plates and cake

[197]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 550.
[198]"Lime Softening Sludge Treatment and Disposal," p 607.
[199]Calkins, p 426.
[200]Calkins, p 427.
[201]Calkins, p 426.

thickness (Figure 17). The concept was first adapted to water treatment in the mid-1960s and full-scale plants were constructed in the mid-1970s.[202]

Filter cake thickness is the most important factor in design of a pressure filter and is standardized at thicknesses of 25, 30, and 40 mm (0.98, 1.18 and 1.57 in.).[203] The proper thickness should be determined by filtration tests.

The filter medium needs cleaning periodically. An acid soaking or recirculation system is usually used to clean calcium carbonate deposits. Precoating the filter with flyash (at a rate of 10 lb of flyash per 100 sq ft of filter area) can lengthen the interval between cleanings by preventing the sludge from contacting the filter.[204] Despite the higher application rate, flyash use may be preferable because it is less costly.

A final solids concentration of 50 percent in the cake is possible, with low suspended solids in the filtrate.[205] The feed is often gravity thickened first to 2 to 6 percent solids.[206]

Pilot studies have shown that conditioning of alum sludge with lime, flyash, or other agents may be necessary. If lime is used, it is added until the pH of the sludge reaches 11, and a reaction time of 30 minutes should be allowed before filtering.[207] Lime may be added in two stages with an interim period when sludge settles and then the clear water can be poured off. This method can result in less overall lime required.[208]

Because of the high pH of the sludge (due to conditioning), the filtrate may contain high concentrations of metal such as aluminum from the coagulant or trace metals from flyash (if used as a precoat). Special treatment may be required before recirculating filtrate to the head of the plant or discharging it.

Disposing of the Solids

Discharge of solids to surface streams is prohibited in most states but several other options are available, including discharge to sewers (although this is not generally permitted), disposing in a landfill, codisposal with other wastes, spreading on farmland, or use in reclamation of strip-mined land.

Environmental laws permit water treatment plant wastes to be disposed in sanitary landfills. Alum and lime sludges tend to be alkaline and would thus neutralize leachate from sanitary landfills. A laboratory study with conditioned alum sludge alone simulated several years of rainfall and leaching.[209] The leachate pH was 9 to 10. Aluminum and chlorides were present in the leachate, but under field conditions these would have been diluted to very low levels. Also, when combined with seepage from the municipal wastes, the leachate would have a more neutral pH and metals concentration would also be lower.

[202]"Water Treatment Plant Sludges--An Update on the State of the Art: Part 2," p 551.
[203]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 552.
[204]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 552.
[205]"Lime Softening Sludge Treatment and Disposal," p 604.
[206]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 553.
[207]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 551.
[208]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 551.
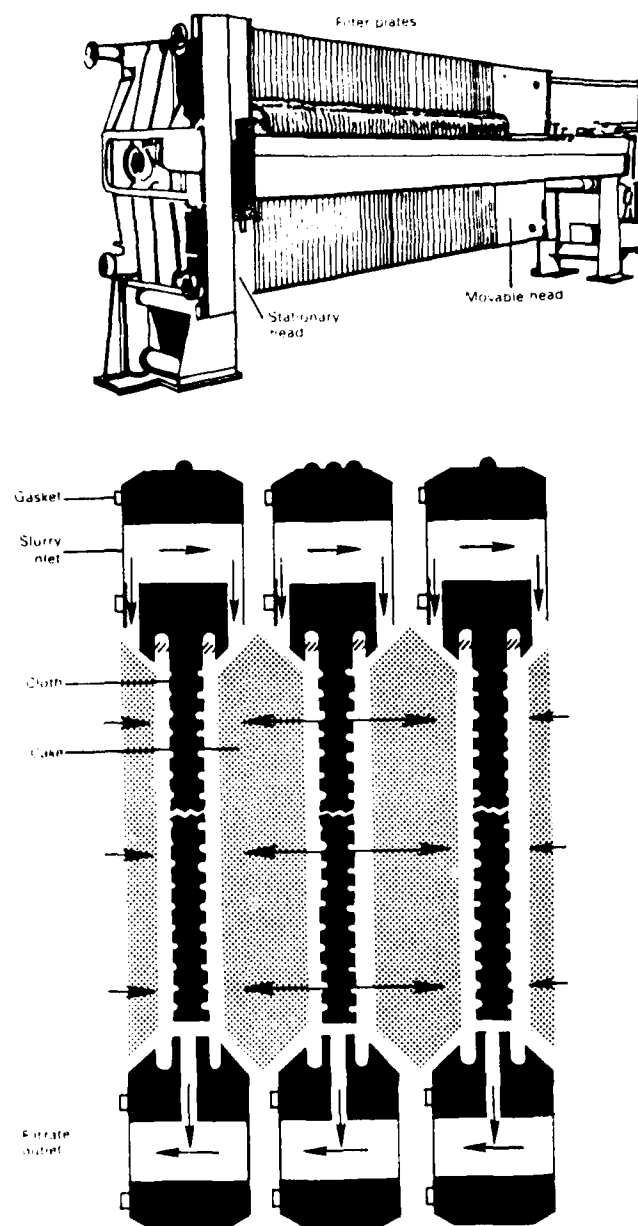[209]"Water Treatment Plant Sludges--An Update of the State of the Art: Part 2," p 553.

Figure 17. **Pressure filter.** (Source: J. W. Clark, *Water Supply and Pollution Control*, Dun-Donnelley, NY, 1977.)

Codisposal of softening sludges with other wastes is another option. Lime sludge could be used to neutralize acidic waste (such as acid from regenerating ion exchange resin), as a bulking agent, or in incineration to produce alkaline ash.[210] Codisposal could involve lime sludge and other wastes generated at the installation or at nonmilitary activities in the region. The most favorable codisposal option would depend on the opportunities available and the feasibility of handling the wastes to make the treatment effective.

In many instances where sludge has been applied to farmlands, it was seen to be more effective at neutralizing soil pH than commercial lime. It can also make the soil more porous, improving drainage and workability. The sludge could be applied as a liquid at 8 to 10 percent solids or dewatered to 40 percent solids and spread.[211] The application would have to be scheduled with farmers' needs but may be a worthwhile disposal option for part of the year. In Ohio, sludge was applied at 6 to 7 percent solids at the rate of 3.5 to 4 tons/acre and no adverse effects on crops were detected.[212]

Lime sludge has been used to reclaim strip-mined land in Ohio.[213] It is applied at 10 tons/acre and is environmentally acceptable as long as the runoff water quality meets stream standards and the operation does not pose safety hazards.

Treating the Supernatant

In many instances the supernatant from treatment of solids is good enough quality to be recycled to the head of the plant. This is actually the intent of the "zero discharge" goal of the Water Pollution Control Act Amendments of 1972. If sludge treatment contributes other contaminants (as in the case of pressure filtration where flyash is used to precoat the filter, or where lime conditioning raises the pH and causes metals to go into solution), further treatment of the supernatant may be required before recycling or discharging. Local authorities would have jurisdiction on discharging this water to sewers.

In many cases, recycling the supernatant with a low suspended solids content can enhance coagulation by either reducing the alum requirements or acting as a seed for precipitation of coagulant products. This was discussed in Chapter 5.

Sludge Pelletization

Sludge pelletization involves a different type of lime softening process: suspended bed cold softening. It produces a smaller amount of more easily dewatered sludge. It is more suited to warmer groundwater with a high calcium content, typically found in the southeastern United States.

The reactor is shaped like an inverted cone and is initially filled about two-thirds full with silica granules, 0.20 to 0.25 mm effective size,[214] which act as a catalyst. Water to be softened continually flows upward in a spiral motion at about 3 ft/min. Lime

[210]"Lime Softening Sludge Treatment and Disposal," p 605.
[211]"Lime Softening Sludge Treatment and Disposal," p 606.
[212]"Lime Softening Sludge Treatment and Disposal," p 606.
[213]"Lime Softening Sludge Treatment and Disposal," p 606.
[214]"Lime Softening Sludge Treatment and Disposal," p 604.

is added at the top and calcium carbonate precipitates on the granules, which increase in size to 0.7 to 1.0 mm. The detention time in the reactor is 8 to 10 minutes[215] and the unit is intended to be operated continuously if the bed volume can be kept constant.

The catalyst granules will last 40 to 60 days before replacement. Finished water turbidity indicates when replacement is necessary. The sludge (spent silica granules) typically has a solids content of 60 percent by weight and will easily dewater to 90 percent solids. The pelletized sludge volume is 10 to 20 times smaller than the sludge from conventional softening treatment.[216]

A suspended bed cold softening reactor is in use at a Marine Corps installation.[217] The silica grains are obtained from the beach at no cost. For 1 mgd capacity, spent granules are replaced every 2 months and hauled by five dump trucks to sludge drying beds at a local sewage treatment plant. In addition, every 2 weeks, one-half a dump truck load of granules is removed from the bottom of the reactor.

Recovery of Chemicals

The technology to recover lime or alum from sludge exists but has not been practiced widely at Army or municipal plants due to high initial capital costs and high energy requirements, and the presence of impurities in the recovered alum or lime.

Lime can be recovered from softening sludge in a process called recalcination.[218] Sludge is first gravity thickened to 18 to 30 percent solids content. It may then be carbonated to redissolve magnesium hydroxide (lowering the magnesium content improves the recalcining effectiveness), followed by centrifuging to 50 to 65 percent solids. It is then burned at 1800 to 2000°F to convert calcium carbonate to calcium oxide and CO_2. The lime and CO_2 produced may then be reused in treatment. It is possible to recover more lime than was initially applied in softening, with a purity of 86 to 93 percent.

Several types of furnaces are available for recalcination: rotary kilns, flash calciner, fluidized bed calciner, and multiple hearth calciner. In 1975 eight water treatment plants in the United States used either the rotary kiln, flash calciner, or fluidized bed calciner.[219] The energy requirements are high: 8.5 to 12 billion Btu/ton to yield calcium oxide with over 90 percent purity.[220]

Alum can be recovered from aluminum hydroxide sludge by adding acid to the sludge and then separating, neutralizing, and dewatering the solids. The Fulton process is based on this technique and then uses a filter press to dewater the sludge. Another new process uses organic solvents to extract aluminum from the sludge and then sulfuric acid to produce alum from the aluminum-solvent mixture.[221]

[215]"Lime Softening Sludge Treatment and Disposal," p 604.
[216]"Lime Softening Sludge Treatment and Disposal," p 604.
[217]J. Chen, Facilities Engineer, Naval Base, Norfolk, VA, Personal Communication (April 30, 1984).
[218]"Lime Softening Sludge Treatment and Disposal," p 605.
[219]The Quest for Pure Water, p 215.
[220]"Lime Softening Sludge Treatment and Disposal," p 605.
[221]The Quest for Pure Water, p 214.

When lime or alum recovered from sludge is reused for softening or coagulation, any impurities such as metals would eventually build up in the system and could present a health problem. Some of the sludge would have to be periodically wasted.

9 IRON AND MANGANESE REMOVAL

Symptoms of Contamination

The presence of iron and manganese in drinking water is usually very obvious. Tap water may be red or black, leaving stains on plumbing and fixtures and on clothing when bleach is added to wash water. At high concentrations (above 2 or 3 ppm), iron and manganese impart a taste to water. Iron bacteria, which thrive on these metals, can grow in the distribution system even at iron concentrations as low as 0.1 ppm.[222] Slimes may grow and consume the chlorine residual, clog pipes, and cause taste and odor problems.

Treatment to remove these contaminants is usually called for if concentrations exceed the USEPA drinking water standards of 0.3 ppm and 0.05 ppm, respectively.

Iron and manganese get into the water supply from natural sources such as dissolution of rocks and soils, from acid mine drainage, or as a result of corrosion. They are found in surface or ground water in soluble form, either as ferrous or manganous ions or chemically bound with organic material.

Sometimes raw water may not contain appreciable amounts of iron and manganese but signs of high concentrations may appear at the tap. In this case, the cause could be corrosion of cast iron pipes by water that has not been stabilized, or bacteria growing in the pipes may be causing even minute amounts of iron and manganese in solution to convert to insoluble form, resulting in precipitation and color problems. Other types of bacteria living off trace amounts of organic material in the distribution system can upset the equilibrium conditions and cause iron and manganese to go into solution or cause taste, odor, and color problems. Chapter 6 should be consulted if stabilization of the water is necessary. Bacterial growth can be controlled by removing dissolved organic matter from the raw water, disinfecting the lines, and keeping iron and manganese concentrations low.

Removal Methods

Iron and manganese removal usually involves converting the metal from the soluble to the insoluble form and then removing it by settling and filtering. There are four main techniques for doing this:

1. Oxidation by chemical addition, then settling and filtering

2. Lime softening followed by settling and filtering

3. Ion exchange

4. Manganese zeolite process.

These are discussed separately in the following sections.

K. J. Ficek, "Potassium Permanganate for Iron and Manganese Removal," *Water Treatment Plant Design* (Ann Arbor Science, 1979), p 472.

Water treatment processes that influence iron and manganese removal are listed in Table 26 along with key O&M criteria. The four techniques listed above make use of these processes, so they should be reviewed with the objective of trying to strengthen the key O&M criteria involved. (Review Table 3.)

Oxidation by Chemical Addition

Oxidation by chemical addition involves converting the iron and manganese from the soluble (Fe^{+2}, Mn^{+2}) to the insoluble (Fe^{+3}, Mn^{+4}) form by adding oxygen, chlorine, or potassium permanganate. The insoluble iron and manganese products (usually hydroxides) are then removed by settling or filtering. This is a popular method and is believed to be the most effective means of removal.[223]

Oxygen may be introduced by aeration, which will strip CO_2 from the water and help raise the pH to the optimum range. The chemical reaction calls for 0.14 mg/L of O_2 to oxidize each mg/L of iron and 0.29 mg/L of O_2 for each mg/L of manganese.[224] Aeration is slower than other chemical methods and is not always effective for lowering the metal concentration.[225]

Many plants practice prechlorination, which oxidizes iron and manganese so they are removed during the normal settling and filtration. Chlorine oxidizes iron at pH 7 to 10 and manganese at pH above 8.5, so pH adjustment is usually necessary.[226] If the point of chlorination is being moved to just before filtration (to avoid formation of THMs), other chemicals such as potassium permanganate ($KMnO_4$) may be needed to effectively oxidize the iron and manganese.

$KMnO_4$ is a very effective oxidizing agent for iron and manganese removal because the chemical reaction is rapid and complete. In theory, 0.91 mg/L of $KMnO_4$ is needed for each mg/L of soluble iron, and 1.92 mg/L for each mg/L of soluble manganese.[227] The pH range needed is 6 to 9, although some researchers say that to oxidize manganese, the pH should be above 10.[228]

$KMnO_4$ may also be considered as an alternative to chlorine in pretreatment to avoid THM problems, as discussed in Chapter 3. It would be mixed in a solution of 1 to 2 percent $KMnO_4$ and fed at the rapid mixer.

Other oxidizing agents that may be used are calcium or sodium hypochlorite and chlorine dioxide. They are not as popular because of the high dosage required and high chemical costs. Also there may be adverse health impacts of hypochlorites reacting with organics and of residual chlorine dioxide.

Iron and manganese removal can be enhanced by improving coagulation once oxidation has taken place. At one plant on Long Island, NY, an anionic polymer was used as a coagulant instead of alum.[229] The anionic polymer more effectively removed the insoluble iron during settling and decreased the loading on the filters.

[223] Ficek, p 472.
[224] Benefield, et al., p 465.
[225] Ficek, p 475.
[226] Benefield, et al., p 476.
[227] Ficek, p 475.
[228] Benefield, et al., p 476.
[229] Prendiville, p 66.

Table 26

Processes Related to Iron and Manganese Problems and Key O&M Criteria

	Treatment Understanding	Process Monitoring and Control	Preventive Maintenance	Analytical Capabilities
Chemical Dosage	x	x		x
Coagulation/ Flocculation		x		
Filtering	x	x	x	
Softening	x	x	x	x
Disinfection	x	x		
Stabilization	x	x		x

The use of oxidizing agents is not effective if the iron and manganese are chemically bound with organic compounds. Conventional turbidity removal processes (coagulation, flocculation and sedimentation, followed by filtration) should remove the insoluble metal-organic complexes.

Lime Softening

The lime or lime-soda softening process removes iron and manganese along with other hardness-causing metals. This process increases the pH, which contributes to removal.

Ion Exchange

Ion exchange resins may be used for removal of soluble iron and manganese. Precautions must be taken to prevent the water from being aerated prior to the ion exchange unit. Otherwise the iron and manganese may be converted to the insoluble form and be deposited on the resin, causing fouling.

Manganese Zeolite Process

In this process the iron and manganese are oxidized to the insoluble form and filtered out, all in one unit. Greensand filter material or other media such as diatomaceous earth, sand, or anthracite are used in the bed. Potassium permanganate, the oxidizing agent, may be continuously fed (in a solution of 1 to 4 percent $KMnO_4$) to the raw water and the insoluble iron and manganese is filtered out.[330] If the filter medium is manganese greensand (which itself can oxidize iron and manganese), the

[330]Ficek, p 475.

potassium permanganate is used to regenerate the greensand. Manganese zeolite has an exchange capacity of 0.09 lb/cu ft and the flow rate to the exchanger is usually 3.0 gpm/sq ft. Regeneration requires approximately 0.18 lb potassium permanganate per cubic foot of resin.[131]

Sequestering Agents

Sequestering agents such as polyphosphates or sodium hexametaphosphate are sometimes used to keep soluble iron and manganese in solution, preventing them from being oxidized and deposited in the treatment plant or on pipes, coloring tap water. TM 5-660 specifies use of 1 to 5 ppm polyphosphate as a sequestering agent when soluble iron is below 2 to 3 ppm.[132]

Polyphosphates have certain drawbacks. In hot water systems, they revert to orthophosphates, which are ineffective as a sequestering agent. If the soluble iron and manganese does get oxidized to the insoluble form in the distribution system, the polyphosphates do not sequester that form, and color problems will result. Phosphates support bacterial growth, so they must be used in limited amounts. (TM 5-660 states that a small amount of hypochlorite should be used to combat this.) Use of polyphosphates to control iron and manganese problems in the distribution system is discussed in Chapter 6.

[131] Benefield, et al., p 476.
[132] Technical Manual 5-660, *Operation of Water Supply and Treatment Facilities at Fixed Army Installations* (Department of the Army, November 1952), p 149.

10 REVERSE OSMOSIS

Reverse osmosis (RO) uses a semipermeable membrane to remove dissolved and minute matter including salts and fluorides, some organic compounds, and bacteria—to produce high quality water. RO is especially applicable if the water supply is seawater or brackish water, or if the supply is high in dissolved solids or ions such as fluoride. Its biggest application is for desalinization.

Only since 1900 have researchers begun to apply RO to water and wastewater treatment, and only in the past 10 years have units been commercially available. Today RO units around the world supply 500 mgd for drinking, commercial, and industrial uses. These units range in size from small (100 gpd) to very large (25 mgd) plants. Florida has more RO units than any other state.[233]

The Reverse Osmosis Process

Osmosis, or the natural passage of material through a semipermeable membrane separating two solutions, has been known for the past two centuries. When a semipermeable membrane (or a membrane that prevents certain sizes or types of particles from passing through it) is placed between a fresh water solution and saltwater solution, water will naturally pass from the fresh water side to the saltwater side until the salt concentration is equal on either side.

In reverse osmosis, a pump applies external pressure to the saltwater solution to make water pass through the membrane from the saltwater side to the fresh water side, opposite to the direction it would naturally flow in osmosis (Figure 18). The result is very pure product water separated from brine (water with high concentrations of salts or other impurities) which could not pass through the semipermeable membrane.

The rate water flows across the membrane depends on the applied pressure; the membrane permeability, area, and thickness; and the osmotic pressure, which originates from the difference in dissolved solids concentration between the two solutions.

The percent recovery, or conversion, expresses the ratio of permeate (product water) to feed water. Recovery rates for reverse osmosis range from 20 to 90 percent depending on the raw water and the arrangement of the units.[234] The amount of a given contaminant removed compared to the amount in the feed water, termed the "rejection rate," is expressed as a percentage. The contaminants are "rejected" because they cannot pass through the semipermeable membrane.

Reverse Osmosis Membranes

Membranes for RO units are usually made from synthetic polymers. Cellulose acetate or cellulose triacetate membranes are most widely used.[235] They are made of

[233] L. E. Applegate, "Membrane Separation Processes," *Chemical Engineering*, Vol. 91, No. 12 (1984), p 74.

[234] Applegate, p 72.

[235] J. W. Clark, *Water Supply and Pollution Control*, Dun-Donnelly, New York (1977), p 477.
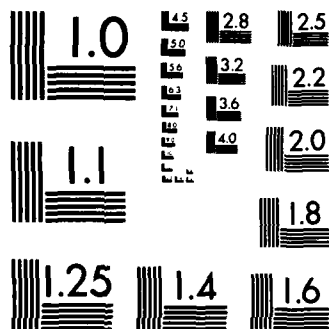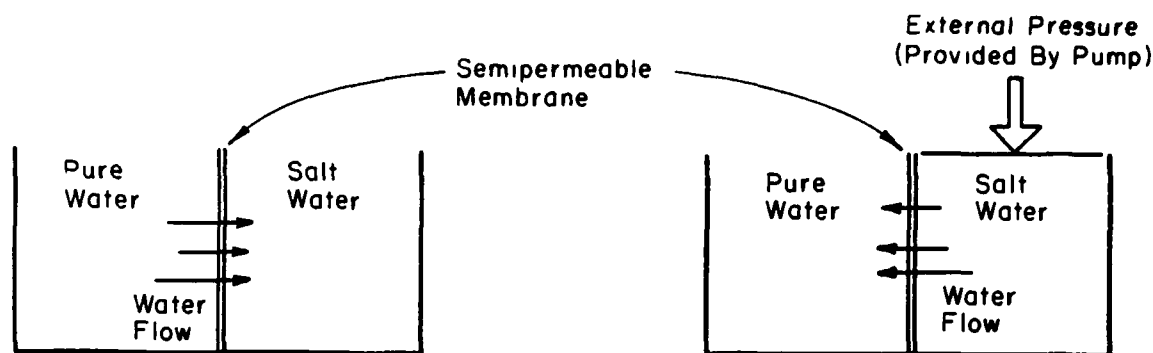
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Osmosis: Water Flows Through Membrane From Pure Water Side To Salt Water Side Until Concentrations Are Equal.

Reverse Osmosis: Salt Water Is Under Pressure So Water Flows From Salt Water Side Through Membrane To Pure Water Side.

Figure 18. Principle of reverse osmosis.

skin about 0.1 to 1.0 μm thick supported by a porous substructure[236] and can filter water at a rate of 10 to 20 gpd/sq ft at a pressure of 400 psig.[237] For the membrane to be effective, temperature, pH, and biological growth must be controlled. At low or high pH levels (< 3 or > 8), cellulose acetate hydrolyzes or reverts to cellulose. Keeping the temperature below 75 to 80°F will extend membrane life.[238] Substances produced by biological growth can attack the membrane, so it is necessary to disinfect the water. This can be a problem, however, because the membranes cannot tolerate prolonged exposure to concentrations higher than 1 mg/L free available chlorine. Brief exposure to 10 to 20 mg/L chlorine is tolerable.[239]

Aromatic polyamide ("aramid") polymer (nylon) membranes are also popular. They too must be operated in a certain pH range (pH 4 to 11) to prevent hydrolysis and biological attack.[240] They are very sensitive to chlorine, and cannot tolerate residuals above 0.1 mg/L.[241]

Cellulose triacetate and polyamide membranes recently have become available in a thin-film composite form.[242] A very thin film (about 200 A°) is formed over a porous incompressible support structure. Those membranes can withstand high pressure and operate under high temperature (up to 120°F) and a wider pH range between pH 2

[236]Applegate, p 67.
[237]I. Nusbaum, "Water Quality Improvement by Reverse Osmosis," *Water Treatment Plant Design* (Ann Arbor Science, 1979), p 625.
[238]Clark, p 478.
[239]Nusbaum, p 625.
[240]Applegate, p 67.
[241]Nusbaum, p 625.
[242]Nusbaum, p 626.

and 12. Although these membranes still must be protected from chlorine, they are more resistant to other oxidizing agents and organic substances. The new type also does not compact as much after normal service as the other membranes do.

Reverse Osmosis Assemblies

Three types of RO assemblies are commercially available: tubular, spiral wound, and hollow fiber.

Tubular

The tubular assembly, developed in the 1960s, is made of strong porous tubes with a cellulose acetate membrane on the inside. Feedwater is pumped into and through the tubes and membrane and is collected on the outside of the tubes. The brine flows out the other end of the tube. Advantages of this assembly are that the brine flow pattern is not complex, the porous tube serves as the pressure vessel, and minimal prefiltration of the feedwater is required. Disadvantages are high capital and operating costs, large volume occupied by the device, and little technology available for membrane replacement.[243] It has been limited to industrial uses.[244]

Spiral Wound

Spiral wound assemblies are more compact: they have a large membrane surface area per given volume of device (250 to 500 sq ft/cu ft).[245] A tricot fabric permeate collector is sandwiched between two flat membrane sheets. These layers are wrapped around a hollow tube, forming a cartridge or element up to 12 in. diameter and 40 in. long.[246] Figure 19 shows a typical cartridge. Feedwater enters one end of the cartridge under pressure and flows through the membrane sheets into the fabric collector, which conducts the clean water to the central tube and out the end of the cartridge. The brine continues through the feed channel spacer along the length of the tube and exits at the opposite end.

Since each cartridge does not convert much water--usually only 15 to 20 percent[247]--up to six cartridges may be connected in series to form devices 22 ft long. This enables recovery rates of 50 to 70 percent for brackish water.[248] Currently, spiral wound assemblies produce 30 mgd worldwide for municipal and industrial uses.[249]

Besides their compactness, other advantages are factory assembly of the cartridges and ease of replacing units in the field. A disadvantage is that the feedwater must be well filtered to prevent blockage of the feed channel spacers.[250]

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[243]Clark, p 479.
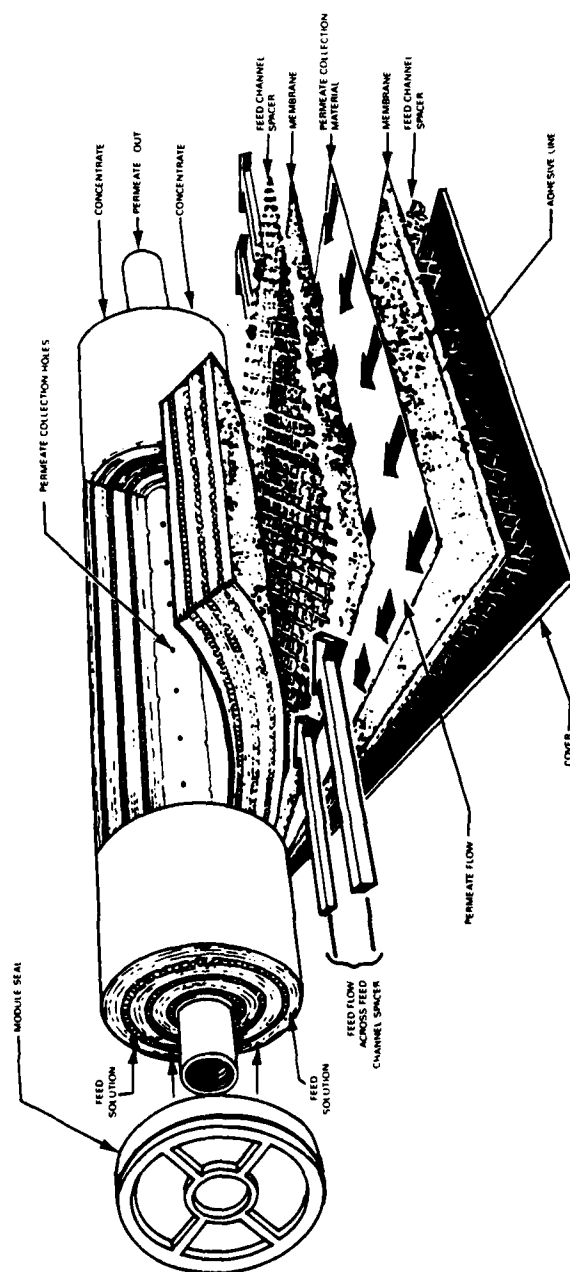
[244]Nusbaum, p 626.

[245]Clark, p 480.

[246]Nusbaum, p 627.

[247]Applegate, p 68.

[248]"The Quest for Pure Water," p 189.

[249]Nusbaum, p 626.

[250]Clark, p 480.

Figure 19. Spiral wound membrane module. (Reprinted with permission from I. Nusbaum, "Water Quality Improvement by Reverse Osmosis," Water Treatment Plant Design, Ann Arbor Science, 1978.)

Hollow Fiber

With hollow fiber assemblies, the aramid membrane itself is formed into minute tubes or fibers. The inner diameter is only 0.0033 in. Feedwater flows from the outside to the inside of the fiber. Up to 4-1/2 million fibers are bundled together, sealed at one end, and inserted into a tubesheet at the other. This assembly is placed in a pressure vessel either 4 or 10 in. in diameter and up to 4 ft long (Figure 20).[251] Feedwater enters the end of the vessel through a central distributor tube. It is forced into the fibers and filtered water is collected at the tubesheet at the other end of the vessel. Brine accumulates outside the fibers and exits a port at the end of the pressure vessel.

Fibers can be made of polyamide polymer or cellulose triacetate. The hollow fiber RO units must be operated above a minimum flow to ensure an even distribution through the fiber bundles and to keep high concentrations of salt from building up next to the membrane. Typically, a single hollow fiber unit can achieve a 50 percent conversion rate to purified water.[252]

As with spiral wound membranes, 30 mgd are currently produced by hollow filter RO units around the world.[253] The hollow fiber devices are more compact, however, with packing densities of 10,000 to 20,000 sq ft membrane/cu ft.[254] Other advantages are that the membrane is so strong that no other support structure is needed, and that a lot of water can be filtered before interference occurs at the membrane surface. Disadvantages are that the water must be well filtered to prevent clogging of the fibers, and that system pressure is limited to 500 psig or less.[255] Also, a large number of tubes are needed and it is hard to spot defective tubes.

RO System Configuration, Design, and Operating Considerations

Configuration

An RO system consists of pretreatment steps, a high pressure pump, the RO device, product water handling and storage, and brine disposal facilities. Figure 21 shows a schematic of a typical single stage RO unit.

The high pressure pump and a pressure-regulating valve on the brine discharge provide the driving force for reverse osmosis. The pump operates at 800 to 1000 psi for sea water or at 400 to 600 psi for brackish water systems.

Other necessary components for the system are high and low pressure switches and high temperature switches to protect the RO unit, pressure indicators before the filter and before and after the pump, and flow meters and pressure indicators on the brine and product water discharge lines. Sample ports should be included on the feedwater, brine, and product water lines, and the product water line should have a drain for use during cleaning.

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[251] Applegate, p 69.
[252] Applegate, p 69.
[253] Applegate, p 69.
[254] Nusbaum, p 626.
[255] Clark, p 481.

Labels (top diagram): Header, Hollow Fiber Cartridge, Polyester Overwrap, Tube Sheet, Header, Brine, Feed, Product Water, Case, Distribution Core, Segmented Ring

Representation of a Hollow Fiber Functioning as a Membrane

Feed, Pressure 400 psi, Product, Brine
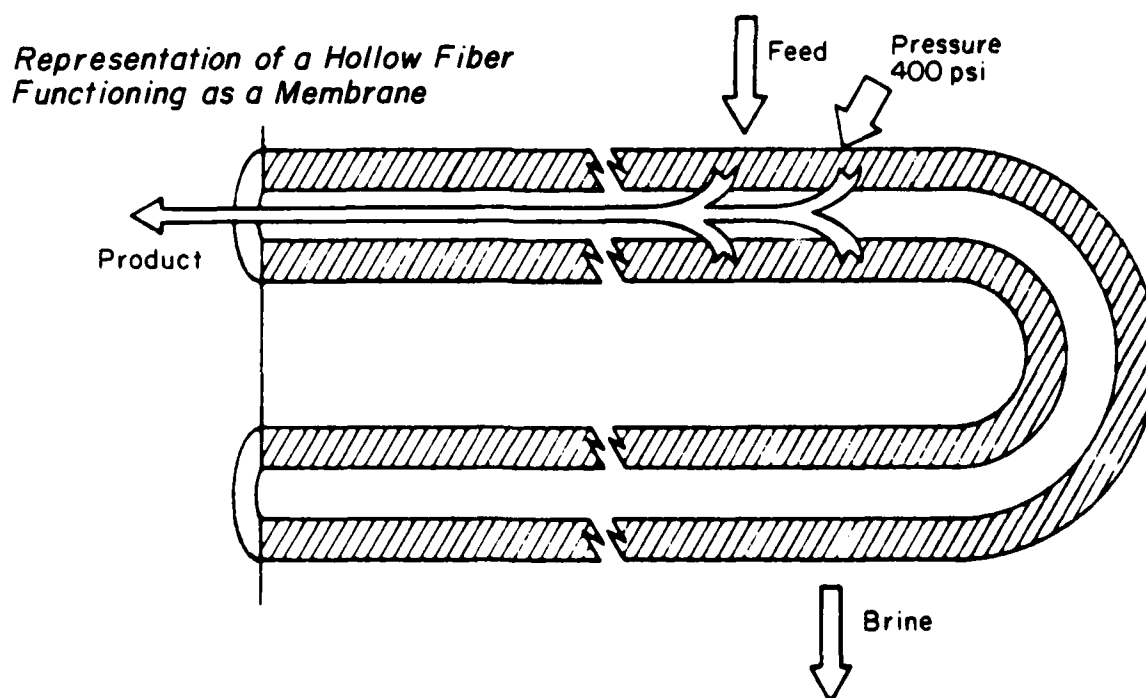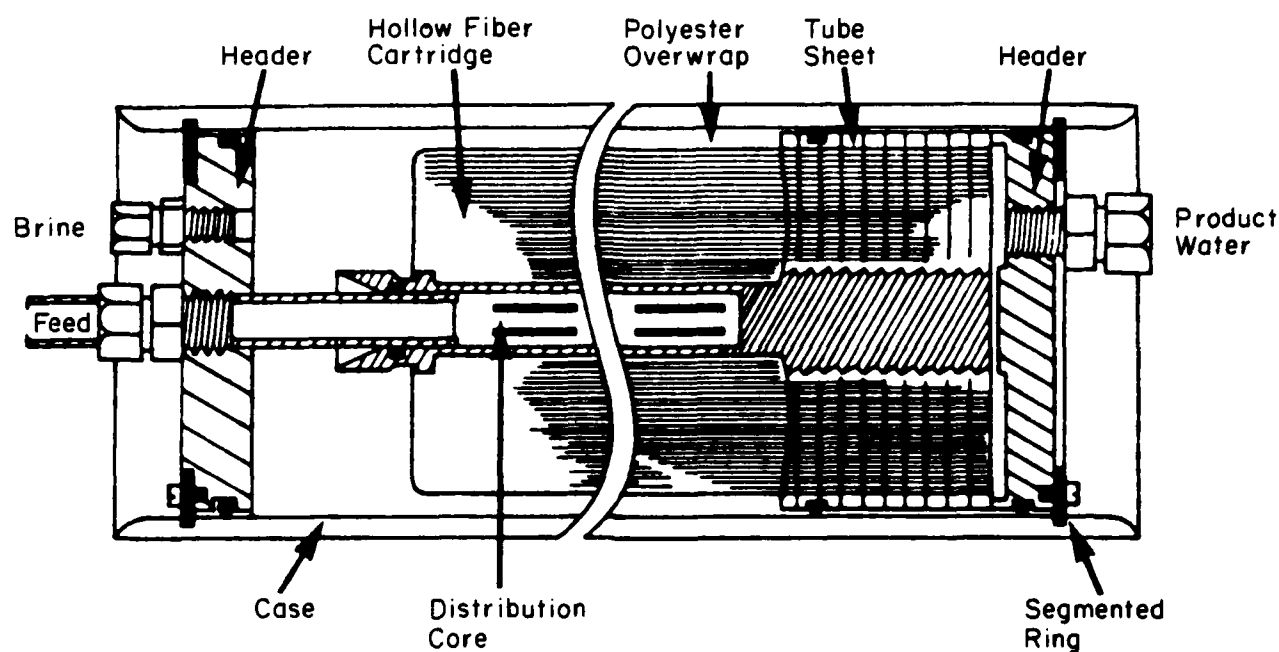
Figure 20. **Hollow fiber reverse osmosis membrane.** (Reprinted with permission from I. Nusbaum, "Water Quality Improvement by Reverse Osmosis," *Water Treatment Plant Design*, Ann Arbor Science, 1978.)
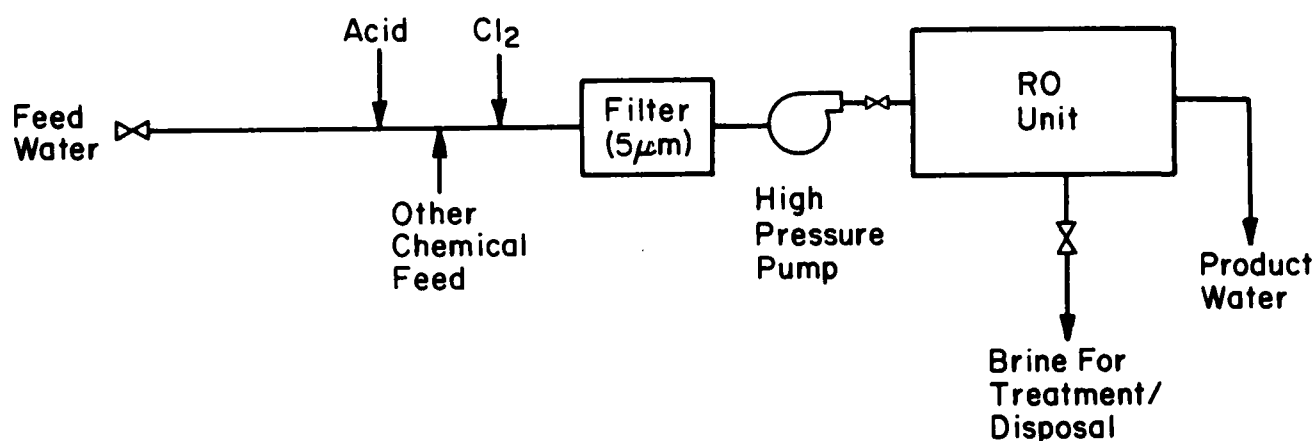
Figure 21. Flow schematic for simple single stage RO unit.

At plants requiring higher product water recovery, two or more stages of units may be needed. There may be six units operating in parallel, followed by three in parallel, then one unit. The permeate from the first two stages can be split and combined with the final product water, as shown in Figure 22.

Design Considerations

When designing or planning a system, a projection[256] should be done to make sure the appropriate RO units and configurations are selected, and that adequate pretreatment is included for product water to meet the desired quality specifications. Information needed for the projection includes design capacity and operating conditions, and a full water quality analysis, as shown in Table 27. Manufacturers often guarantee a certain product water design flow for a given number of years, such as 3 to 5 years.[257] These considerations affect the design and operation of the system, treatment effectiveness, and capital and operating costs.

Another design consideration is the materials. Corrosion resistant or noncorrosive materials should be used for piping and pumps, as corrosion products could cause membrane fouling.[258] Low pressure piping should be made of PVC, polyethylene, fiber-reinforced polyester, or epoxy fiberglass. High-pressure pipes for seawater should be made of 304 or 316 stainless steel, and for brackish water, 316 or 317 stainless steel. Linings and coatings for pipes and connections in the pretreatment system should be nonmetallic, such as phenolics, epoxies, or rubber.

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[256]Nusbaum, p 648.
[257]Applegate, p 72.
[258]Applegate, p 72.
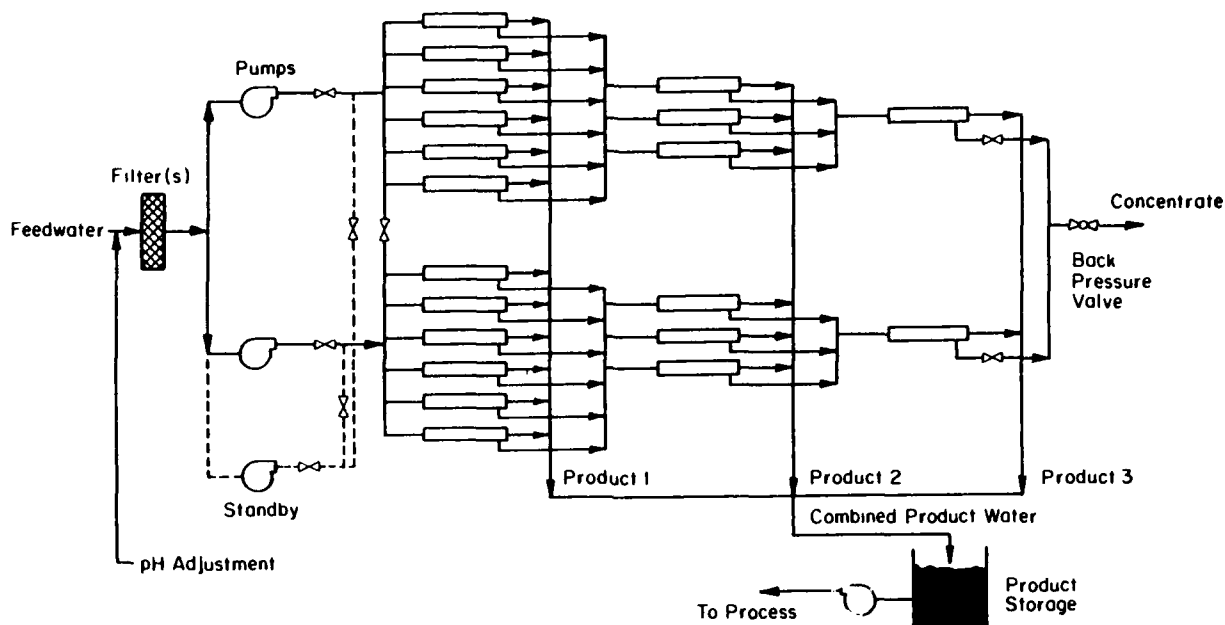
Figure 22. Reverse osmosis units in parallel and in stages. (Reprinted with permission from I. Nusbaum, "Water Quality Improvement by Reverse Osmosis," *Water Treatment Plant Design*, Ann Arbor Science, 1978.)

Pretreatment

Pretreatment should not be overlooked when designing or operating an RO system. Water fed to RO units must be treated adequately to prevent clogging of the assembly, to prevent membrane fouling by biological growth or chemical precipitation, and to protect the membrane from high or low pH.

Pretreatment usually includes filtration, pH adjustment, coagulation, disinfection, and sometimes dechlorination and deaeration. Sodium hexametaphosphate may be added to prevent precipitation of calcium sulfate. If the water has a high concentration of organics that the membrane will not remove, carbon adsorption or some other organics removal mechanism may also be needed.

The pretreatment required depends on the quality of the feedwater, the type of RO membrane and assembly and operating conditions such as conversion rate. A pilot test may be necessary to determine proper treatment.

Particulate and colloidal matter should be removed in pretreatment to avoid clogging the assembly. The hollow filter assemblies need the most pretreatment to avoid problems with colloids, followed by spiral wound and hollow tube assemblies.[259]

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[259]Applegate, p 71.

Table 27

**Design and Operating Information Needed for
Projection of RO System***

Minimum and Maximum Feedwater Temperatures

Product Water Design Capacity

System Recovery Rate

Pressure of Feedwater and Product Water

Ca^{+2}	Cl^-
Mg^{+2}	F^-
Na^+	CO_3^{-2}
K^+	PO_4^{-3}
Sr^{+2}	NO_3^-
Ba^{+2}	SiO_2
Fe^{+2}	CO_2
HCO_3^-	pH
SO_4^{-2}	Brine Flow Rate

*Reprinted by permission from *Chemical Engineering*, Vol. 91, No. 12 (1984), L. E. Applegate, "Membrane Separation Processes," p 72.

Manufacturers will often specify a maximum level allowed in the feedwater--given in terms of turbidity or silt density index (determined by operating a 0.45 μm filter at 30 psig and measuring the rate of filter clogging). Small particles (5 to 25 μm are removed by a cartridge filter.[260] The disposal filter is changed when the pressure drop across it reaches a certain level.

It is essential that the salts in the feedwater, such as sulfates or silicates, do not precipitate on the membrane, causing scaling. Scaling is prevented by changing the solubility of the salt so precipitation does not occur. For example, to prevent $CaCo_3$ scaling on brackish or seawater RO systems, acid is added to lower the pH to a range where $CaCO_3$ is soluble. At the 5 mgd water reclamation plant in Orange County,

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[260]Applegate, p 70.

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California,[261] H_2SO_4 is added to reduce the pH and alkalinity corresponding to a pH of 5.5. This shifts the carbonate forms to bicarbonate and CO_2, preventing scaling and helping extend the life of the membrane.

At the 45,000 gpd plant in Charlotte Harbor, Florida, the feedwater pH is adjusted to between 5 and 6[262] to prevent $CaCO_3$ scaling. (The acid is added at the discharge side so that standard construction materials could be used for the pump.) Acid is usually added to adjust pH at plants with cellulose acetate membranes, which can only tolerate a pH range of 3 to 8, and pH adjustment or ion exchange is used to prevent scaling on units with polyamide or thin film composite membranes.[263]

Another benefit of adding acid and sodium hexametaphosphate is to prevent oxidation of soluble ferrous and manganous ions in the raw water to the insoluble state.[264] If these ions are kept soluble, they will not precipitate and cause fouling on the membrane.

Brackish water will probably need lime or ion exchange softening or sodium hexametaphosphate addition to prevent scaling by calcium sulfate, barium sulfate, strontium sulfate, and calcium fluoride. A chemical feed system was included at the Charlotte Harbor, Florida, plant to raise the concentration of sodium hexametaphosphate to 5 to 7 mg/L.[265] Sulfate salt scaling may also be prevented by lowering the system's conversion rate to slow the buildup of salt concentrations near the membrane.[266]

Brackish water will also need pretreatment to control silica (SiO_2) scaling. This can be done by lime-soda ash softening to remove the silica, by increasing the temperature (within a range tolerated by the membrane) to change solubility, or by changing the conversion rate to prevent high silica concentrations near the membrane.[267]

Biological fouling must also be controlled, usually by adding low doses of chlorine. Since chlorine concentrations above 0.1 mg/L cannot be tolerated by polyamide membranes and the new thin film composite membranes,[268] chlorine must be removed as part of the pretreatment. Polyamide membranes can be shock treated with $NaHSO_3$, I_2 or H_2O_2 to control biofouling.[269] Other practices to stop biological growth would be to flush out the system with purified water when the plant is out of service for more than 10 days, and as the final step in cleaning.[270]

Carbon adsorption or other mechanism may be needed to remove organics that may attack the membrane or cause it to swell and lose effectiveness. If there are organic compounds in the raw water, the manufacturer should be consulted to see if they could

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[261] D. G. Argo, "Wastewater Reclamation by Reverse Osmosis," *Water Pollution Control Federation Journal*, Vol. 51, No. 3 (1979), p 595.

[262] M. R. Huxstep, *Inorganic Contaminant Removal from Drinking Water by Reverse Osmosis*, Cooperative Agreement No. RC-805207 (USEPA and MERL, February 1981), p 16.

[263] Applegate, p 70.

[264] Nusbaum, p 640.

[265] Huxstep, p 16.

[266] Applegate, p 70.

[267] Applegate, p 70.

[268] Nusbaum, p 625.

[269] Applegate, p 71.

[270] Argo, p 595.

cause a problem. A pilot study may be needed to see if and which special pretreatment for organics removal is necessary.

Energy Requirements

Energy requirements for RO systems vary widely, depending on whether the feed is sea water or brackish water, the overall system configuration, and whether the pumps are high or low pressure. Typical energy requirements are 6 to 8 kwh/1000 gal for brackish water and 35 to 40 kwh/1000 gal or lower for new seawater plants.[271] Some energy can be recovered by passing the brine flow through a turbine; this is more feasible at seawater plants where brine flow may be three quarters of the feed flow and is discharged from the RO unit at very high pressure (750 to 950 psig).[272] Energy recovery can reduce costs by as much as 17 percent.[273]

Capital and Operating Costs

Capital cost depends on the system capacity, the feedwater and desired product water quality, and system configuration. Capital cost generally includes site development, intake structures or wells, pipelines and transfer pumps, pretreatment facilities, high pressure pumps, RO devices, brine discharge facilities, and product water treatment and storage facilities. The RO units alone generally account for between 10 and 30 percent of the capital cost.[274] Table 28 gives approximate capital and operating costs.

Desalinization

High salinity is characteristic of some Army water supplies. "High salinity" may refer to sea water, which has a total dissolved solids (TDS) concentration of about 35,000 mg/L, or brackish water, which has a TDS ranging from 1000 to 15,000 mg/L. Although there are a number of methods to remove salinity, reverse osmosis is used most often at Army water treatment plants.

Sea water, which has a TDS concentration of about 35,000 mg/L, can be desalinated to an acceptable TDS level using a high pressure RO system. High pressure systems usually operate at 800 to 1000 psig.[275] More likely, sea water would be desalinated in multi-staged units, called product staging.[276] The first stage reduces the TDS level toaround 725 mg/L, and half of that water goes through a second stage. The final product is combined to result in a final TDS concentration of under 500 mg/L.

Brackish water can have TDS concentrations ranging from 1000 to 15,000 mg/L.[277] Reverse osmosis units to treat this water operate at pressures up to 400 to 600 psig.[278]

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[271]Applegate, p 73.
[272]Applegate, p 73.
[273]Applegate, p 77.
[274]Applegate, p 76.
[275]Applegate, p 73.
[276]Applegate, p 72.
[277]Huxstep, p 1.
[278]Applegate, p 73.

Table 28

Typical Costs for RO Plants*

	Capital Costs	Operating Costs Per 1000 Gallons
Brackish Water Plants (Feedwater TDS 2000-5000 mg/L, 80% conversion. Plant capacity 95%)		
25 mgd	$0.82/gal/day	$1.11
1 mgd	$1.20/gal/day	$1.54
Seawater Plants (Feedwater TDS 35,000 mg/l, 30% conversion. Plant capacity 85%)		
5 mgd	$4.40/gal/day	$5.32
1 mgd	$8.37/gal/day	$9.04

Note: All calculations assume a feedwater temperature of $21^{\circ}C$, minimum pretreatment and no energy recovery. Operating costs would be reduced by 17% with energy recovery. Energy requirement assumed 38 kwh/1000 gal.

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*Reprinted by permission from *Chemical Engineering*, Vol. 91, No. 12 (1984), L. E. Applegate, "Membrane Separation Processes," pp 76-77.

Other Reverse Osmosis Applications

Reverse osmosis can also be used to purify water high in dissolved solids and to remove many types of inorganic compounds, some types of organic compounds, bacteria, viruses, and radioactive material. Fluoride, nitrate, arsenic, and many other salts are removed. Table 29 shows rejection rates for 25 compounds, typical of what could be achieved by a commercially available unit operating at a net pressure of 400 psi.[279]

Fluoride removal by reverse osmosis can be very effective; vendors claim rejection ranges ranging from 40 to 96 percent. For brackish water with fluoride concentrations up to 112 mg/L, 45 to 90 pecent rejection can be achieved, depending on the pH.[280] A pilot plant in Charlotte Harbor, Florida, was able to reduce 4.7 to 12.5 mg/L fluoride in well water to below the drinking water standard using a high pressure (400 psig) unit.[281]

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[279]Nusbaum, p 631.
[280]T. J. Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," *JAWWA*, Vol. 78 (1978), p 112.
[281]Huxstep, p 26.

Table 29

Rejection of Rate of Compounds by Reverse Osmosis

Rejection of Various Compounds at 400 psi (2800 kN/m^2) Net, pH 5 to 6

Compound	Rejection %	Compound	Rejection %
LiCl	96.4	SiO_2	92.3
NaF	97.1	H_3BO_3	44
NaCl	96.0	NH_4Cl	93.3
NaBr	92.3	$CuCl_2$	98.9
NaI	88.9	$CuSO_4$	99.6
$NaNO_3$	93.3	$NiCl_2$	99.4
$NaHCO_3$	97.4	$NiSO_4$	99.9
KCL	95.5	$FeCl_2$	99.7
$NaSO_4$	99.6	$AlCl_3$	99.2
$MgCl_2$	98.8	CO_2	0
$CaCl_2$	98.8	H_2S	0
$MgSO_4$	99.8		
NaH_2PO_4	99.8		

*Reprinted with permission from I. Nusbaum, "Water Quality Improvement by Reverse Osmosis," *Water Treatment Plant Design*, Ann Arbor Science, 1978.

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13 CONCLUSION

This study identified water treatment plant processes at Army installations which may be inadequate for meeting recent regulatory requirements, developed a method for relating water treatment processes with treatment plant inadequacies, and identified design and O&M criteria and new technologies that could solve problems and improve performance.

It was found that Army water treatment plants are most likely to experience regulatory difficulties in the following areas: corrosion, sludge handling and disposal, iron and manganese removal, trihalomethanes, fluoride removal, salinity removal, nitrate removal and coagulation/flocculation/filtration. (Trace organics were also identified as a problem area and are covered in USA-CERL TR N-85/11.)

A method was developed which will enable installation personnel to relate the above problems to specific water treatment processes and to identify and evaluate O&M criteria at their own facilities which could be changed to solve treatment problems and improve overall performance.

METRIC CONVERSIONS TABLE

1 in.	= 2.54 cm
1 ft	= .305 m
1 lb	= .453 kg
1 oz	= 28.35 g
1 gal	= 3.78 L
1 sq ft	= .093 m^2
1 cu ft	= .023 m^3
1 psi	= 6.89 kPa
°F	= (°C x 9/5) + 32

Bottled Water

Bottled water could be made available at the installation for those families that need it. Considering the high capital and O&M costs of community-size nitrate removal plants and home treatment units, this would probably be the most efficient and cost effective method of providing water that meets the drinking water standards for nitrates.

Table 33

Capital and O&M Costs for Nitrate (1983)

Plant Capacity, gpd	Capital Costs*		O&M Costs**	
	Ion Exchange	Reverse Osmosis	Ion Exchange	Reverse Osmosis
50,000	65,000	78,000	68	117
100,000	74,000	131,000	41	92
250,000	98,000	245,000	22	69
500,000	129,000	430,000	15	57
750,000	170,000	625,000	13	52
1,000,000	221,000	776,000	13	49

*Includes site preparation, equipment, housing construction materials, piping, electrical material and instrumentation, and labor.
**Includes material, energy and labor but not regeneration and brine disposal.

Reprinted with permission from Scranton Gillette Communications, Inc., T. J. Sorg, "Compare Nitrate Removal Methods," *Water and Wastes Engineering*, Vol. 17, No. 11, pp 29-30.

The cost for the canister of ion exchange resin and faucet is about $450 and the fee for regeneration is about $48.[313] A disposable resin cartridge is also available at about $300 initially ($35 for subsequent replacements).

Home-size RO units consist of a 5-cartridge filter, a reverse osmosis membrane, a small storage reservoir, a charcoal filter, and a faucet. They produce about 8 to 11 gpd, and cost about $700.

Since RO membranes are more sensitive to impurities, additional pretreatment may be needed. The water would have to be softened and iron removed if the concentration is higher than 0.5 mg/L of iron. Chlorine removal may also be necessary, depending on the type of membrane. Some vendors offer a combination softener/iron removal ion exchange tank with automatic salt regeneration. This is a separate tank costing about $800 to $1000, which would bring the total cost per home up to $1500 to $1700.

O&M costs would be for salt to regenerate the softener/iron removal unit, $50 to replace the cartridge every 6 to 10 months, and about $100 every 2 years to replace the membrane.

[313]Hays, Culligan Water Systems, Champaign, IL, Personal Communication, September 14, 1984.

reduced to below 10 mg/L. This represents a 76 to 80 percent rejection rate (amount of contaminant removed compared to the amount in the raw water). RO membrane vendors claim that rejection rates are typically 60 to 95 percent.[310] Laboratory studies conducted by adding nitrate to the raw water in levels up to 250 mg/L showed a 68 to 73 percent rejection using a single stage unit.[311]

In deciding between ion exchange and RO treatment for nitrate removal, quality of the raw water is an important consideration. Table 27 listed parameters needed in designing the RO system. The chemical analysis would be equally valuable for an ion exchange unit. Examining water quality will indicate how effective nitrate removal will be (for example, how quickly an ion exchange bed will be exhausted or how easily a membrane will become fouled), what pretreatment is needed (such as iron, hardness, or chlorine removal) and what the operating costs will be.

Capital and O&M Costs

Table 33 shows capital and O&M costs for nitrate removal by ion exchange and reverse osmosis. The largest part of the capital cost is for the vessels and automatic controls; the largest O&M costs are salt used for regeneration and resin replacement every 5 years. Regeneration and brine disposal costs are not included under O&M because these depend on water quality, how the unit is operated, and site constraints. Regeneration costs for ion exchange will increase with sulfate concentration in the raw water. Assuming 100 percent removal efficiency of sulfate and nitrate, 15 lb salt/cu ft resin is the amount estimated to be needed.[312]

Small-Scale Treatment Alternatives

Because high nitrates are of concern to such a small portion of the population, it may be more economical and efficient to provide bottled water or install nitrate removal units in the homes of families with pregnant women or infants under 6 months rather than treat water at the plant level.

Home Units

Small RO or ion exchange nitrate removal units are available at a cost between $450 and $2000 each, depending on the raw water quality. Some units can be installed under a kitchen counter and come with a separate tap.

A home-size ion exchange unit consists of 0.25 cu ft of strong acid-strong base resin packed in a 6-in. diameter, 18-in. tall canister. The resin is nonselective, in that it removes all ions, including those contributing to hardness. If the water is hard, the resin will be exhausted sooner. The exchange capacity of a typical canister of resin is about 2500 grains of hardness as $CaCO_3$. The resin can be regenerated and reused for 10 to 20 years before replacement is necessary. Regeneration could be done by the vendor or by technicians at the installation.

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[310]Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 108.

[311]Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 108.

[312]Sorg, "Compare Nitrate Removal Methods," p 31.

Table 32

Processes Related to Nitrate Removal and
Key O&M Criteria

	Treatment Understanding	Process Monitoring and Control	Preventive Maintenance
Membrane (Reverse Osmosis)		x	x
			፤
Ion Exchange	x	x	

The system was installed at the well and operated automatically "on demand" without storage facilities. USEPA is continuing work on this project in an attempt to improve the process and lower operating costs.

A 1200 gpm ion exchange plant removes nitrate from ground water in Nassau County, New York, at the Garden City Park Water District. The water supply contains 20 to 30 mg/L of nitrate and is reduced to below 2 mg/L.[309] This plant efficiently removes nitrates because the sulfate concentration of the raw water is low--around 30 to 40 mg/L. (The exchange resins naturally prefer to remove sulfates over nitrates.) TDS concentration is also a factor.

Research is now underway to develop a resin that is selective for nitrate ions. Sulfate and silica can both reduce the exchange capacity of resin. Work is also being done to develop and optimize the regeneration scheme. This would involve operating the beds in a partially regenerated mode or using continuous regeneration.

A full water quality analysis should be made in specifying an ion exchange removal system. A pilot study may also be recommended in designing a system.

Reverse Osmosis

Reverse osmosis (RO) can also remove nitrates effectively. The water is pumped through the assembly at high pressure and nitrate ions and other impurities pass through a semipermeable membrane, leaving pure water. Several types of membranes and RO assemblies are available for use as a single stage or in series of stages. Pretreatment, including filtration, pH adjustment, and possibly softening, is also needed. Chapter 10 described the components of RO plants and O&M information.

While RO plants have not been installed solely for nitrate removal, pilot plant measurements and laboratory studies have demonstrated that nitrate levels can be brought below the 10 mg/L Drinking Water Standard. At the 45,000 gpd pilot plant in Charlotte Harbor, Florida, nitrate levels ranging from 15 to 41 mg/L in raw water were

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[309]*Compare Nitrate Removal Methods*, "Water and Wastes Engineering," Vol. 17, No. 12, p 28.

12 NITRATE REMOVAL

Regulatory Limits

High nitrate concentration is of concern because of serious health risk to infants less than 6 months old and pregnant women. Nitrates are converted to nitrites, which combine with hemoglobin in the blood to result in methemoglobinemia, a condition that can cause suffocation and death. Infants are more susceptible than adults because the bacteria that convert nitrates grow more readily in an infant's digestive tract.

The current USEPA MCL for nitrates in drinking water is 10 mg/L of nitrate nitrogen, or 45 mg/L nitrate. Nitrates reach drinking water supplies--usually ground water-- mostly from agricultural activity. High nitrate concentration was noted as a problem at one U.S. installation and is also a problem at posts in the Federal Republic of Germany.

The usual approach to dealing with nitrate contamination is to provide the susceptible families with bottled water. However, nitrate removal methods are also described here in the event an alternative to bottled water is sought.

Treatment Plant Removal Methods

Conventional water treatment methods such as turbidity removal and lime softening are not effective or practical for removing nitrates.[308] Biological denitrification of nitrate to nitrogen gas is also impractical. Membrane separation techniques such as electrodialysis and ultrafiltration can remove nitrates but there is little operating experience with these processes specifically for nitrate removal.

Ion exchange and reverse osmosis are the two most commonly used methods for nitrate removal. Table 32 shows important O&M criteria for these two processes.

Ion Exchange

Ion exchange involves passing the water through a resin which removes NO_3^- ions. When the exchange capacity of the bed is exhausted it is regenerated with a salt solution and the resulting effluent must be disposed of, usually in an evaporation pond.

Equipment needed includes pretreatment equipment; vessels and resin (at a community plant more than one unit is installed so one is in service while the other is being regenerated); a brine tank and brine disposal facilities; controls; pumps; and piping.

Water must be pretreated to remove particulates, iron, and hardness to prevent fouling of the resin. If the water is high in dissolved iron that is oxidized, it would precipitate within the bed. Backwashing may not remove heavy deposits.

Pilot studies were done by USEPA at a 1 mgd capacity plant in California, where nitrate level in the well water was 16 mg/L. Seventy percent of the water was treated to 2.6 mg/L, then blended with raw water to a final concentration of 6.6 mg/L NO_3-N.

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[308]Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 107.

Activated alumina beds are usually 5 ft deep, with two or more beds per installation, and are operated at 5.0 to 7.5 gal/min-sq ft. Optimal pH for removal is 5 to 6, with exchange capacities at this pH range of 2000 to 4000 grains/cu ft.[303]

Regenerating the bed involves an upflow backwash with raw water for 10 minutes (to remove trapped solids), followed by upflow regeneration with 1 to 2 percent NaOH solution at 2.5 gal/min-sq ft for about 35 minutes.[304] This is followed by an upflow rinse at 5.0 gal/min-sq ft for about 30 minutes and a downflow regeneration step with 1 to 2 percent NaOH solution. Since this leaves the bed with a high pH, it must be neutralized with low pH rinsewater before being returned to service.

The operating costs for activated alumina beds, including chemicals, electricity, bed replacement, replacement parts and labor, range from 8 to 20 cents per 1000 gal.[305] Operating costs for the plants in Arizona and California (0.7 mgd and 1.5 mgd, respectively), were 15 to 20 cents per 1000 gal treated.[306]

One potential problem in operating an activated alumina bed is that fluoride measurements of treated water can be subject to error. The analytical method may use a colorimetric procedure, which is subject to interferences by aluminum unless the sample is distilled.[307] This would result in measured fluoride values being lower than the actual fluoride concentration in the treated water.

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[303]Benefield, et al., p 415.
[304]Benefield, et al., p 413.
[305]Benefield, et al., p 415.
[306]T. J. Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 111.
[307]Bellen, et al.

turbidity removal would be needed to remove even a small amount of fluoride.[297] PAC was successful at removing fluoride only at a very low pH.

Some fluoride is removed during lime softening but only if enough magnesium is present, so this method also has not become popular.

Very few data are available on experiments or actual plants using electrodialysis for fluoride removal. Compared to ion exchange, the equipment is more expensive.

Reverse osmosis can remove fluoride effectively, but few plants installed have been solely for that purpose. As with electrodialysis, the costs are relatively high. If the fluoride is to be removed along with other contaminants, reverse osmosis may be a viable alternative. More information on RO systems and plant experiences in removing fluoride was presented in Chapter 10.

Ion exchange is the most effective and popular method of fluoride removal. Bone char, synthetic resins, and activated alumina have been used.

Bone char, or ground bones charred to remove organic materials, was used at a plant in South Dakota to treat raw water with an average fluoride content of 6.7 mg/L to a finished water concentration of 1.5 mg/L.[298] The exchange capacity of bone char at this plant was 102 g fluoride removed per cubic meter of bone char, for water with 5 mg/L fluoride.[299] A disadvantage is that bone char loses its exchange capacity after several regeneration cycles. Also, it is soluble in acid so the pH must be controlled during the last rinse after regeneration.

Synthetic ion exchange resins have been tested, but are not as popular as activated alumina. Experience with the synthetic resins showed a gradual pH increase in the finished water.[300]

Activated alumina, composed of hydrated alumina, is granular and porous and has about the same density as bone char and synthetic resin. It is less expensive, however ($12 to $15/cu ft, compared to $38 to $48/cu ft for bone char and $125 to $150/cu ft for strong base resin).[301] It also has a strong preference for adsorption of fluoride over other anions (such as sulfates, iodide, chloride, nitrate, etc.) It is available in standard mesh sizes and has been used for other commercial and industrial processes.

An activated alumina ion exchange plant was operated successfully in Bartlett, Texas, for about 25 years and newer plants have been operated in California and Arizona.[302] The fluoride concentration in the water at these plants was reduced from a range of 5 to 8 mg/L to below 1 mg/L.

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[297] Bellen, et al., p 109.
[298] Benefield, et al., p 411.
[299] T. J. Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," *JAWWA*, Vol. 70 (1978), p 110.
[300] Benefield, et al., p 410.
[301] T. J. Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 108.
[302] Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 111.

Table 30

Maximum Contaminant Levels for Fluoride*

Temperature (°F)	Fluoride Concentration (mg/L)
53.7 & below	2.4
53.8 - 58.3	2.2
58.4 - 63.8	2.0
63.9 - 70.6	1.8
70.7 - 79.2	1.6
79.3 - 90.5	1.4

*National Interim Primary Drinking Water Regulations, 40 FR 141, December 4, 1975.

Table 31

Processes Related to Fluoride Removal and Key O & M Criteria

	Treatment Understanding	Process Monitoring & Control	Preventive Maintenance	Analytical Capabilities
Coagulation/ Flocculation		x		
Softening	x	x	x	x
Reverse Osmosis	x	x	x	
Ion Exchange	x	x		

11 FLUORIDE REMOVAL

Fluoride is found in the earth's crust, in sea water at a concentration of 1.4 mg/L, and in ground water at concentrations as high as 9 to 10 mg/L.[292] It may also be introduced to drinking water supplies as a waste product from industrial activities such as fertilizer manufacturing.

Limited amounts of fluoride in the diet help prevent tooth decay, but too much can cause mottling of the teeth. High concentrations over extended periods can cause changes to the bones, serious dental fluorosis, and possible kidney damage.[293]

Regulatory Limits

Table 30 shows USEPA limits on fluoride concentration, which range from 1.4 to 2.4 mg/L, depending on ambient temperature.[294] Most of the water supplies exceeding these standards are groundwater sources in the midwest and western United States, primarily in Arizona, Colorado, Illinois, Iowa, New Mexico, Ohio, Oklahoma, California, South Dakota, and Texas.[295] At the end of the 1970s about 1500 communities had drinking water containing fluorides in excess of the Drinking Water Standards.[296]

Removal Methods

A number of techniques for fluoride removal have been tested:

● Coagulation with alum

● Coagulation with powdered activated carbon (PAC)

● Lime softening

● Electrodialysis

● Reverse osmosis

● Ion exchange.

Table 31 shows how these removal methods are reflected in treatment processes and the important O&M criteria. These O&M criteria should be carefully reviewed in selecting a removal method, in order to get the most benefit from treatment.

Alum coagulation and PAC have not been widely used because of practical considerations. Studies have shown that much higher alum doses than are normally used for

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[292]Benefield, et al., p 405.
[293]G. E. Bellen, M. Anderson, R. A. Gottler, *Performance and Cost of Two Activated Alumina Defluoridation Treatment Plants, National Sanitation Foundation,* p 1.
[294]National Interim Primary Drinking Water Regulations, 40 FR 141, December 4, 1975.
[295]Benefield, et al., p 411.
[296]"The Quest for Pure Water," p 167.

pressure and flow indicators--are familiar to operators and make it easy to learn the system.

Future developments will result in lower capital and operating costs for RO systems. New types of membranes and assemblies will be less costly and allow units to operate at higher conversion rates and under a wider variety of environments. Improvement in pretreatment will also help reduce operating costs, improve effectiveness, and prevent fouling. Other improvements will be lower energy requirements, which also mean lower costs.

(The Interim Primary Drinking Water Standard for fluoride ranges from 1.4 to 2.4 mg/L depending on temperature.) This represents a 90 to 93 percent rejection.

Vendors claim that nitrates can be removed at 60 to 95 percent rejection rates,[282] although nitrate removal is not the primary purpose of most RO installations. Laboratory studies with NO_3-N added to the feedwater at concentrations of 2.5 to 250 mg/L showed 68 to 73 percent rejection using a single-stage unit.[283] At the Charlotte Harbor pilot study, rejection rates of 76 to 80 percent were seen at raw water concentrations of 15 to 41 mg/L. There was no problem meeting the Drinking Water Standard of 10 mg/L using the high pressure (400 psig) unit.[284]

Reverse osmosis can remove large, complex organic compounds such as nitrogen-based organics that interfere with chlorination, lignins, humic and fulvic acids, methylene blue active substance (MBAS), and compounds causing color problems.[285] Organic compounds with low molecular weight (below 120) that are water soluble usually cannot be removed,[286] so a pilot study should be done if these are of concern. Phenols, chlorinated hydrocarbons, halogenated compounds, pesticides, and certain types of alcohol are also not removed well.[287] Some organics can damage the membrane, so it is wise to run tests if there is any doubt.

Bacteria, viruses, and fungi can be removed to a certain extent, depending on the membrane condition. Some organics can pass through imperfections in the membrane and grow on the backing. Since the total surface area of the membrane is large, bacterial slimes and molds can easily become attached and proliferate, causing fouling. Also, the enzymes produced by the organisms can attack the membrane.[288] Periodic flushing and disinfection is necessary to keep organisms in check. Some plants chlorinate continuously at a residual of about 0.5 mg/L to control bacteria,[289] but residual levels should be monitored because chlorine can attack the membrane.

RO Advantages

RO units, although not found at most Army water treatment plants, can solve certain water treatment problems such as saline or brackish water, and water high in fluorides, nitrates, or other dissolved solids. These systems are compact and have high availability--85 to 95 percent.[290] The system's modular configuration allows operators to remove only a portion from service for maintenance or repair and keep a part of the system on line. The units can be started up in less than an hour after shutdown,[291] and can be made to shut down automatically in the event of malfunction. Labor and maintenance requirements are low, since the units, once properly installed and operated, need little attention. The relatively simple components--acid feed system, filter, pumps, and

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[282]Sorg, p 108.
[283]Sorg, "Treatment Technology to Meet the Interim Primary Drinking Water Regulations for Inorganics," p 108.
[284]Huxstep, p 29.
[285]Nusbaum, p 637.
[286]Nusbaum, p 637.
[287]Nusbaum, p 637.
[288]Nusbaum, p 648.
[289]Argo, p 593.
[290]Applegate, p 76.
[291]Applegate, p 73.

Huxstep, M. R., *Inorganic Contaminant Removal From Drinking Water by Reverse Osmosis*, Cooperative Agreement No. RC-805207 (U.S. Environmental Protection Agency [USEPA] and Municipal Environmental Research Laboratory [MERL], February 1981).

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